GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: October 2, 1978

Project Title: Graphical and Tabular Results of Computer Simulation of Faulted URD Cables

Project No: E-21-635

Co- **Project Directors:** Dr. E. B. Joy; Dr. A. P. Meliopoulos, Dr. R. P. Webb

Sponsor: Electric Power Research Institute

Agreement Period: From 6/19/78 Until 6/19/79 (Agreement Period) July 11-79

Type Agreement: EPRI Project RP797-2

Amount: $61,170 (Partially funded at $37,000 through 12/31/78)

Reports Required: Forecast of Expenditures; Monthly Project Status Reports; Monthly Financial Reports; Computer Program; User's Manual; Final Report with Handbook

Sponsor Contact Person (s):

Technical Matters

(Project Manager)
T. J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, CA 94303

Contractual Matters
(thru OCA)

Ms. Virginia Hess
Contracts Department
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, CA 94303

415/855-2207

(NOTE: EPRI Project RP797-1 was GIT E-21-679)

Defense Priority Rating: N/A

Assigned to: Electrical Engineering (School/Laboratory)

COPIES TO:

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Gr Ck Co.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: October 17, 1980

Project Title: Graphical and Tabular Results of Computer Simulation of Faulted URD Cables

Project No: E-21-635

Co-Project Director: Dr. E. B. Joy; Dr. A. P. Meliopoulos, Dr. R. P. Webb

Sponsor: Electric Power Research Institute

Effective Termination Date: 7/11/79

Clearance of Accounting Charges: ______

Grant/Contract Closeout Actions Remaining:

X Final Invoice and Closing Documents

_ Final Fiscal Report

X Final Report of Inventions

X ~~Govt.~~ Property Inventory & Related Certificate

_ Classified Material Certificate

_ Other ______

Assigned to: Electrical Engineering (School/Laboratory)

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CA-4 (1/79)

E-21-635

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

.EPHONE: (404) 894-2901

July 19, 1978

MEMORANDUM

TO: EPRI File

FROM: Roger Webb

SUBJECT: First Monthly Status Report, RP797-2

---

1. The project was iniated June 19, 1978. Initial efforts have been to:

   (a) Begin modularization of the existing program in preparation for program additions and expansion.

   (b) Review and evaluate EPRI work statement.

   (c) Begin technical developments necessary to model the 3000 ft. cable length and to accomodate the attendent computational burden.

2. A project initiation meeting was held at Georgia Tech July 11, 1978. Attending were Mr. Tom Kendrew of EPRI and Ed Joy, Sakis Meliopoulos and Roger Webb of Georgia Tech. The following points were discussed:

   (a) Georgia Tech will submit a revised budget to reflect changes in salary and benefit schedules which have occurred since the proposal was submitted. No change will be requested in the fiscal 1978 allocation.

   (b) The number of segments used in the cable model will be chosen to optimize program efficiency while maintaining computational accuracy.

   (c) Ground rod separations of 200, 400, and 1000 feet will be simulated.

   (d) The layer depth in the two layer soil model will be treated as a variable.

   (e) The program will be designed to accomodate variable source impedance. Specific cases will be selected for the study to represent nominal standard operational conditions.

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TELEPHONE: (404) 894-2901

July 19, 1978

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the first Monthly Status Report for RP797-2.

Thank you for coming by last week.

Sincerely yours,

Roger P. Webb
Professor and
Associate Director

RPW:kkm

Enclosure

(f) Fault location with respect to ground rod location will be varied in the study.

3. The crucial element in the project is presentation of sensitivity data. Consequently, effort will be concentrated as soon as practical on making sensitivity studies to:

   (a) Define the various combinations of parameters which must be varied.

   (b) Identify suitable formats for presenting the data in the handbook.

RPW:kkm

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

LEPHONE: (404) 894-2901

E-21-635

August 21, 1978

MEMORANDUM

TO: EPRI File

FROM: Roger P. Webb

SUBJECT: Second Monthly Status Report, RP797-2

---

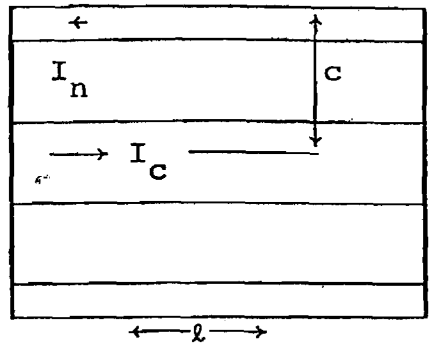
1. Modularization of the existing program has continued. Also, new input/output routines are being developed to accommodate a minimal configuration of 3000 feet of cable with 15 ground rods.

2. New developments underway to accommodate the increased program requirements are:

    a. The procedure for calculating resistance between pairs of cylindrical conductors has been upgraded. The new procedure computes the resistance as the ratio of the average voltage along a given segment induced by the current in the second segment to the current in the second segment. Previously, only the value at the center of the segment was employed. Using the average voltage significantly improves the accuracy of the calculation.

    b. The effect of return currents through neutral and earth on cable impedance (inductive effects) is being modeled. Induced voltage can be represented as

$$V_c = (I_n \ln \frac{c}{d} + (I_c - I_n) \ln \frac{D}{d}) \frac{\mu \ell}{2\pi}$$



d = conductor GMR

c = neutral radius

D = effect geometric mean distance of earth return current path

Use of the effective distance D is an approximation required for computational purposes. Emperical values will be employed for D.

c. A nodal analysis method is being developed to represent the circuit compromising the cable segments and the connection to the external circuit. This technique will enable more detailed segment models and will not be limited to radial systems.

3. A paper is being prepared for possible submission to EPRI concerning application of the program to computation of surface potentials in substation grounding grids. A copy of the proposed paper will be sent to EPRI for review.

RPW:kkm

cc: E. B. Joy
A. P. Meliopoulos

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

-EPHONE: (404) 894-2901

E-21-635

September 26, 1978

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the third Monthly Status Report for RP797-2.

Sincerely,

Roger P. Webb
Professor and
Associate Director

RPW:kkm

Enclosure

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TELEPHONE: (404) 894-2901

September 26, 1978

MEMORANDUM

TO: EPRI File

FROM: Roger P. Webb

SUBJECT: Third Monthly Status Report, RP797-2

1. The procedure for calculating the mutual resistance between parallel conductor segments, including the important case of colinear orientation, has been upgraded, tested and programmed. The procedure for calculating the mutual resistance between orthogonally oriented conductors was revised, but was found not to be reciprocal as it should be. Alternative procedures are currently being developed and tested.

2. Effort has proceeded on circuit modeling. The model to be employed will represent the substation and its grounding system, a cable section comprising n segments and m ground rods of two segments each. The fault segment will be located x units from one end of the cable and the fault modeled as a cylindrical plasma. An equivalent circuit for each cable segment will interface with the electromagnetic computation. A modified nodal analysis has been developed to represent the composite system. This involves generating an admittance matrix for the network. Using this formulation, currents in the system and in earth can be calculated and used to compute surface potentials.

   Current efforts are aimed at exploiting sparse properties of the admittance matrix formulation to reduce computational effort and at implementing and testing the computations.

RPW:kkm

cc: E. B. Joy
    A. P. Meliopoulos

E-21-633

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

EPHONE: (404) 894-2901

October 23, 1978

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the fourth Monthly Status Report for RP797-2.

Sincerely,

Roger P. Webb
Professor and
Associate Professor

RPW:kkm

Enclosures

cc: E. B. Joy
A. P. Meliopoulos

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TELEPHONE: (404) 894-2901

October 23, 1978

MEMORANDUM

TO: EPRI File

FROM: Roger P. Webb

SUBJECT: Fourth Monthly Status Report, RP797-2

---

1. An improved procedure for computing mutual resistance has been developed and is undergoing testing. The upgraded analysis determines and uses the average voltage along the center line of the conductor instead of the voltage at the center point employed previously. For conductors which are widely separated these two voltages are approximately equal, but for closelyspaced, short conductors the two voltages may be as much as 25% different. The new formulation using the average conductor voltage is now being tested against known cases presented in books by Tagg and Sunde.

2. Circuit model development has proceeded. The model, together with a nodal analysis for computation of current flow, has been programmed and is being debugged and tested.

3. Work has begun on identifying and implementing appropriate output formats for computed data.

4. Due to equipment problems, the NOVA 830 computer has been unavailable for the past month. Development has proceeded using the Georgia Tech Cyber system. The NOVA machine should be available soon and enable more expeditious program development.

RPW:kkm

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

LEPHONE: (404) 894-2901

E-21-635

November 22, 1978

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the fifth Monthly Status Report for RP797-2. In addition, enclosed for your information is a proposal I am sending to Flordia Power & Light Company.

Sincerely yours,

Roger P. Webb
Professor and
Associate Director

RPW:kkm

Enclosures

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TELEPHONE: (404) 894-2901

November 22, 1978

MEMORANDUM

TO: EPRI File

FROM: Roger P. Webb

SUBJECT: Fifth Monthly Status Report, RP797-2

---

1. The mutual resistance procedure has been tested and is yielding correct answers.

2. Development of the circuit model has been completed.

3. Validation of the composite program has been initiated.

4. The NOVA 830 system is again operable and developments are proceeding on that machine.

5. Plans are to begin production runs as soon as the program is validated. It will be necessary to define data formats by early February.

RPW:kkm

cc: E. B. Joy
A. P. Meliopoulos

E-21-635

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TELEPHONE: (404) 894-2901

January 7, 1979

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the sixth Monthly Status Report for RP797-2. I apologize for its being late. Also attached is a paper describing our network model which was prepared for the upcoming IEEE Southeastcon Conference.

Sincerely yours,

Roger P. Webb
Professor and
Associate Director

RPW:kkm

Enclosures

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TELEPHONE: (404) 894-2901

January 7, 1979

MEMORANDUM

TO: EPRI File

FROM: Roger P. Webb

SUBJECT: Sixth Monthly Status Report, RP797-2

---

1. The mutual capacitance equations have been derived between any two cylindrical conductors. The cylindrical conductors must be either x, y, or z directed and can be in either of the two conducting earth layers. The permittivities (dielectric constants) of the two layers may be different.

2. Validation of the program has continued. For long circuits, it has been found necessary to use the CDC computer to achieve sufficient accuracy in the solution. Accordingly, a program is being implemented on the CDC. Simulation of long cables will then be a two step process with the solution for current distributions done on the CDC and the network model on the NOVA.

RPW:kkm

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

EPHONE: (404) 894-2901

February 2, 1979

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the seventh Monthly Status Report for RP797-2.

Sincerely,

Roger P. Webb
Professor and
Associate Director

RPW:kkm

Enclosure

cc: E. B. Joy
A. P. Meliopoulos

L 21-602

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

TELEPHONE: (404) 894-2901

February 2, 1979

MEMORANDUM

TO: EPRI File

FROM: Roger P. Webb

SUBJECT: Seventh Monthly Status Report, RP797-2

---

1. Model Development

The mutual impedance equations have been derived, programmed, and tested. The capacitive part of the mutual and self impedances of the segments was found to be five to six orders of magnitude less important than the resistive part.

2. Productive Runs

Production runs employing the complete model are in progress. The earlier problem regarding computational accuracy for systems of large extent have been resolved. The resolution consists of separating the computation into two parts: computation for segment impedances and the network computation to define potentials. The first part is solved using the CDC computer, with the remaining calculation performed on the Nova minicomputer. For production runs, the logistics of this procedure do not represent a significant problem.

3. Report Format

Some proposals for the format will be made at the forthcoming meeting at EPRI.

RPW:kkm

E-21-635

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

.EPHONE: (404) 894-2901

March 14, 1979

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the eighth Monthly Status Report for RP797-2.

Sincerely,

Roger P. Webb
Professor and
Associate Director

RPW/mcs

Enclosure

cc: E. B. Joy
A. P. Meliopoulos

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

LEPHONE: (404) 894-2901

March 14, 1979

MEMORANDUM

TO: EPRI File

FROM: Roger P. Webb

SUBJECT: Eighth Monthly Status Report, RP797-2

---

1. At the meeting at EPRI on Feb. 26 the following proposed outline for the handbook was generally agreed upon.

Proposed Handbook Outline

It is proposed that the handbook include a rather extensive introductory section which defines parameter sensitivities, provides a rationale for the data formats and defines handbook utilization factors. The proposed outline is:

I. Introduction
   - A. Purpose of handbook
   - B. Model definition and general program description
   - C. Problem parameters
     - a. Determinants of at-fault potential
     - b. Determinants of earth currents
     - c. Determinants of earth surface potentials
     - d. Parametric effects
       - i. Circuit parameters
       - ii. Cable parameters
       - iii. Earth parameters
       - iv. Grounding configurations
       - v. Fault location

II. Handbook Utilization Factors
   - A. Required user supplied parameters
   - B. Preliminary calculation for handbook entry
   - C. Data interpretation
   - D. Example

Appendix I. Insulated Cable Data

Appendix II. Bare Concentric Neutral and Semiconducting Jacketed Cable Data

Proposed Data Format

1. Entry Procedure

   a. Cable type
   b. Cable size
   c. Nominal burial depth
   d. Nominal earth resistivity (range)
   e. Fault location

2. Data Format

   For the condition defined in (1), a family of curves, parametric in soil parameters, defining surface potentials normalized to at-fault voltage will be presented. On each curve is tabular data defining earth return impedance Z_G from point of fault (See attached example.)

3. Data Utilization

   a. Calculate at-fault voltage. The procedure will be specified and will require the following data:

      i. System voltage
      ii. Overhead feeder positive and zero sequence impedance
      iii. Cable conductor and sheath resistance

   b. Read normalized step and touch potentials

   c. Multiply by at-fault voltage.

2. Computer runs for several conditions have been made and analyzed. Two conclusions based on this analysis which impact slightly the proposed data format have been drawn.

   i. For any point x_0 along the buried cable, the maximum (3 foot) step potentials in either the x or y directions do not occur with respect to the point $(x_0, y=0)$ but with respect to a point off the cable center line $(x_0, y=y_1)$. (The distance y_1 depends on soil parameters and is in the order of three feet or less.) This can be explained by the fact that surface equipotentials are symmetric about the cable center line and the potential gradient is larger off the center line.

   ii. Irrespective of the absolute magnitudes of the soil layer conductivities σ_1 and σ_2, the step and touch potentials normalized to at-fault voltage depend only on the ratio σ_1/σ_2. The earth return impedances which determine the at-fault voltage however depends on the magnitude of σ_1 and σ_2.

   Regarding the first point, it is proposed that for each distance x_0 in the regions where data is to be plotted (either end and at-fault), the maximum step potential will be computed and plotted. Thus for each x_0, two potentials will be plotted - the touch potential at a point directly above the cable $(x_0, y=0)$, and the maximum step potential.

   The impact of the second point is that the computation of at-fault voltage and use of the curves to determine resultant step and touch potentials can be functionally separated. That is, for all ranges of σ_1 and σ_2, the same set of normalized potential curves parametric in the ratio σ_1/σ_2 can be used. For each of three ranges of conductivity magnitudes (high, medium, and low), tabular data will be provided to enable determination of at-fault voltage.

E-21-635

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

HONE: (404) 894-2901

April 13, 1979

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303

Dear Mr. Kendrew:

Enclosed please find the ninth Monthly Status Report for RP797-2.

Sincerely,

Roger P. Webb
Professor and
Associate Director

/mcs

Enclosure

cc: M. S. Florence
E. B. Joy
N. McHan
A. P. Meliopoulos

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

PHONE: (404) 894-2901

April 13, 1979

MEMORANDUM

TO: EPRI File

FROM: R. P. Webb

SUBJECT: Ninth Monthly Status Report, RP797-2

---

1. Software for data plotting is being developed. Specific cases are being run in order to arrive at final data format specifications.

2. Work has begun on writing the appendix for the final report which will include derivation and definition of the mutual resistance and capacitance equation.

3. Work has been initiated on writing the introductory section of the report.

/mcs

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

PHONE: (404) 894-2901

May 23, 1979

E-21-635

Mr. Thomas J. Kendrew
Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, California 94303

Dear Mr. Kendrew:

Enclosed please find the tenth Monthly Status Report for RP797-2.

Sincerely,

Roger P. Webb
Professor and
Associate Director

cs

enclosure

cc: M. S. Florence
E. B. Joy
N. McHan
A. P. Meliopoulos

xc: Mr. Becker

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL ENGINEERING
ATLANTA, GEORGIA 30332

-EPHONE: (404) 894-2901

May 23, 1979

MEMORANDUM

To: EPRI File

From: R. P. Webb

Subject: Tenth Monthly Status Report, RP797-2

---

1. Program development has been completed. Data plotting is being done on a Calcomp and in a format such that Calcomp plots can be used in the final report.

2. All the cases to be studied have been defined. They span over the parameter ranges specified in the proposal. Preparation of input data for these cases is under way.

3. Production runs are being made.

4. Final report writing is underway.

5. Attached is a sample computer plot.

cs

attachment

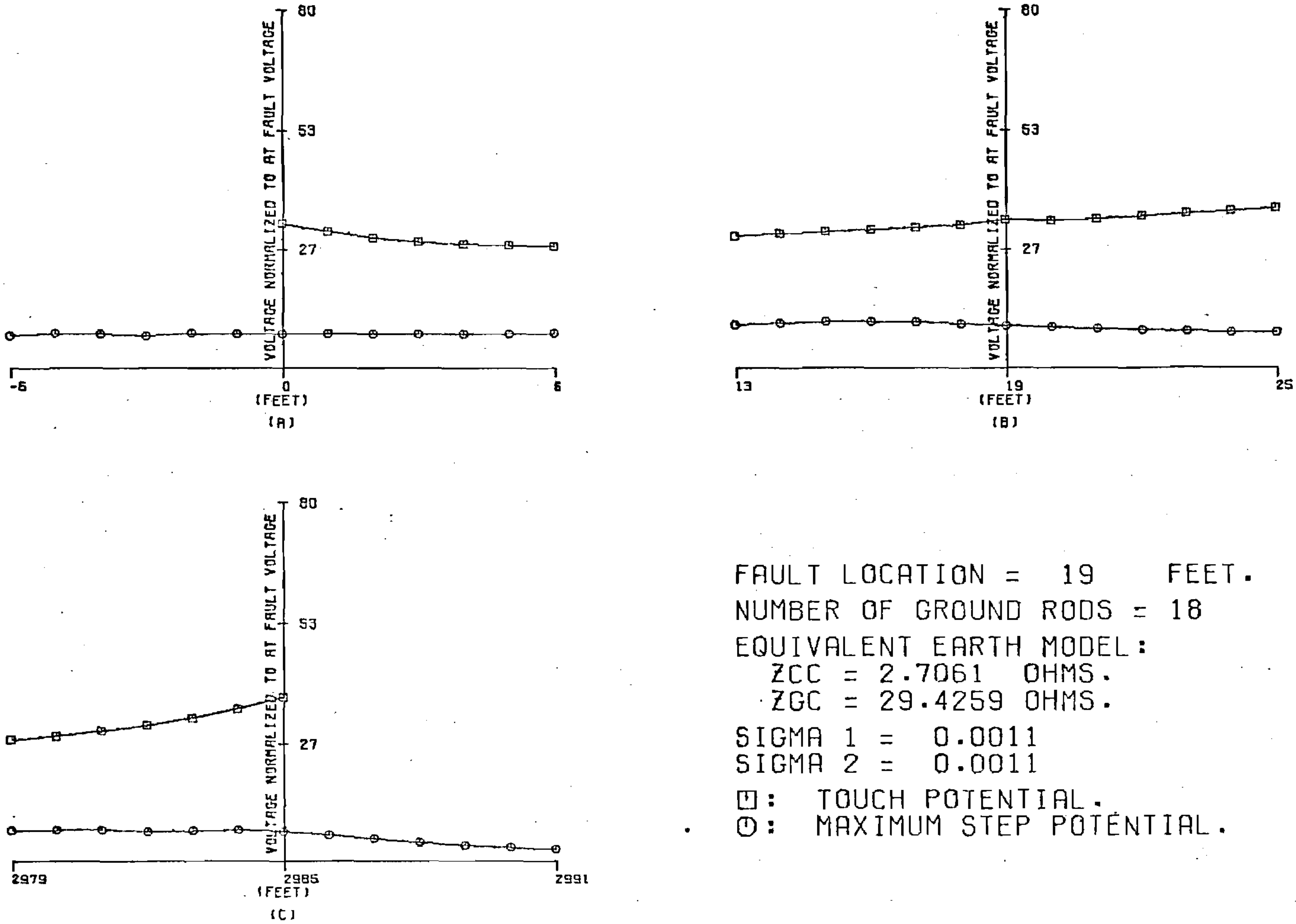


FIGURE TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

EPRI E-21-635

CONTRACTOR COST PERFORMANCE REPORT

EPRI 177 11/78

(All dollar figures should be rounded to the nearest thousand)

CONTRACTOR		ADDRESS	DATE	REV. NO.
Georgia Institute of Technology		Atlanta, Georgia	1/15/79	
CONTRACT COST LIMITATION $61,170	CONTRACT NO. RP797-2	CONTRACT TITLE Graphical & Tabular Results of Computer Simulation of Faulted URD Cables	REPORT PERIOD 6/19/78 to 6/19/79	

Total Contract Cost Plan	Year 19 78												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Approved Forecast							2,912	2,912	2,912	4,219	4,006	5,657	22,618
Current Estimate													

Contractor Actual Incurred Cost	Year 19__												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Monthly Increment							2,912	2,912	2,912	4,219	4,006	5,657	22,618

Remarks: (comment briefly on significant changes)

Review comments and instructions on the reverse side before completing report.

DATE FORECAST APPROVAL (EPRI Project Manager) DATE

Graphical and Tabular Results of Computer Simulation of Faulted URD Cables

Volume 1: Theory and Program Documentation

EPRI

EPRI EL-1605
Volume 1
Project 797-2
Final Report
June 1981

Keywords:
Cable
Concentric Neutral
Corrosion
Underground Distribution
Touch and Step Potential

Prepared by
Georgia Institute of Technology
Atlanta, Georgia

ELECTRIC POWER RESEARCH INSTITUTE

Graphical and Tabular Results of Computer Simulation of Faulted URD Cables
Volume 1: Theory and Program Documentation

EL-1605, Volume 1
Research Project 797-2

Final Report, June 1981

Prepared by

GEORGIA INSTITUTE OF TECHNOLOGY
Electric Power Laboratory of the
School of Electrical Engineering
Atlanta, Georgia 30332

Principal Investigators
E. B. Joy
A. P. Meliopoulos
R. P. Webb

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
T. J. Kendrew

Distribution Program
Electrical Systems Division

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NOTICE

Prepared by
Georgia Institute of Technology
Atlanta, Georgia

ABSTRACT

A method for computing shield potentials of underground residential distribution (URD) cable shield potentials is presented. Earth potentials in the vicinity of the buried cable are also computed. The method utilizes a numerical solution of Laplace's equation to account for earth currents, and a modified nodal analysis method to account for conductor and shield currents as well as inductive coupling in the underground cable system. A computer program has been developed capable of analyzing long lengths of URD cable together with existing ground rods, faults, open neutrals, feeding substation, and substation grounds. The system analyzed corresponds to practical URD cable distribution systems. Extensive simulation of various URD cable systems in various soil environments has been performed and the results tabulated. The simulation program employed and the applicable theory is documented in Volume 1 of this report. In Volume 2 of the report, the simulation results are documented in handbook form. From these graphs and tables, "touch and step" potentials on the earth surface can be determined for various cable types, network connections, and soil types.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report is a follow-on to RP797-1, which described a general computer program to calculate "touch and step" potentials of faulted underground residential distribution (URD) cables. The computer program, entitled BCAB, permits the simulation of URD cable faults for a wide variety of cables, soils, and excitation parameters. Although the BCAB program is a very valuable analytic tool, it requires approximately 30 complex input parameters for each case studied. RP797-2 extends the usefulness of the BCAB program by expanding the program and by computer simulation. It also resulted in a handbook of curves and graphs from which "touch and step" potentials may be determined for a wide variety of faulted URD cable conditions.

PROJECT OBJECTIVE

The purpose of this project was to modify the BCAB program and use the computer to develop appropriate curves and charts that define the fault behavior of URD cables for a wide class of cables, impedances, and soil conductivity values.

PROJECT RESULTS

The results of this project are presented in two volumes. Volume 1 describes in detail the expanded simulation program used to generate the handbook data. The expanded program can be employed for special problems not covered by the handbook. Volume 2 is an engineer's handbook from which "touch and step" potentials may be determined, using curves and graphs, for a wide variety of URD cable fault conditions.

T. J. Kendrew, Project Manager
Electrical Systems Division

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Section I.1

INTRODUCTION AND SUMMARY

1.1 BACKGROUND

This is the final report of the Electric Power Laboratory of the School of Electrical Engineering at Georgia Tech on EPRI Project RP797-2, "Graphical and Tabular Results of Computer Simulation of Faulted URD Cables." The objective of the project was to develop a set of data, based on computer simulation, which defines surface potentials resulting from underground faults for a wide class of cables and applications.

Extruded solid dielectric cables with bare concentric neutral wires have received wide industry acceptance for underground residential distribution primary construction. The performance of this type of cable has been outstanding since the early 1960's. However, incidences of corrosion of the bare copper concentric neutral wires have caused the utilities to consider methods of mitigating the corrosion process. One viable method to control the corrosion is to apply an appropriate semiconducting or insulating jacket over the neutral wires. However, the effect of the jackets was not known.

EPRI Project RP671-1 developed data on "touch and step" potentials when the jacketed neutral cables are subjected to short-circuit conditions at normal operating voltage. It should be noted that this data is applicable only to the one set of system and environmental conditions that prevailed at the Franksville, Wisconsin, test site. To broaden the usefulness of this data, Project RP797-1 was initiated. As a result, "touch and step" potentials can now be investigated at any location. The objective was to develop a general computer program to calculate "touch and step" potentials, using the Franksville test data as a basis for verifying the program. An additional objective was to compute earth surface potentials resulting from operation with an open neutral.

The resultant computer program, entitled BCAB, permits the simulation of URD cable faults for a wide variety of cables, soils and excitation parameters. The program has been validated against actual field measurements and, with the proper selection of input data, can be used for simulations of rather general distribution systems. However, the use of the developed program requires approximately thirty

(30) input parameters for each case studied. Therefore, a more powerful and easier to use tool would be a set of graphs and tables for URD cables, from which step and touch potentials for the wide variety of conditions actually found in practice could be determined.

The objective of this project then has been to extend the usefulness of the BCAB program by using the computer to develop appropriate data to define the fault behavior of URD cables for a wide class of cables, impedances and soil conductivity values. This has been accomplished by extending the previously developed BCAB program to simulate more general utility system distribution configurations and to use the extended program to develop data for general use. The data is presented as Volume II of this report in the form of a handbook which provides the practicing engineer with a quick and easy way of estimating the expected level of earth potentials at the vicinity of buried electrical systems. At the same time, it provides information as to the dependence of earth potentials on various system parameters, such as soil resistivities, system impedances, grounding system, etc. Considerable effort has been devoted in order to simplify the handbook usage as much as possible. Plots of touch and step potentials are provided for a wide range of parameter values. It is expected that most systems encountered in practice fall generally within the range of the data provided.

The expanded simulation program used in generating the handbook data together with an outline of the approach and applicable theory is documented in Volume I of this report. For special problems, not covered by the handbook data, this expanded simulation program can be employed.

1.2 SUMMARY

The end product of this effort is the data compiled in Volume II. These data are in the form of graphs from which, for a given cable type, soil parameters and connected network, the touch and step potentials on the earth surface in the cable vicinity can be determined. Specifically, the touch potentials and maximum step potentials in three regions along the cable are defined.

The salient features in the computation and tabulation of these results can be summarized as follows:

a) A two-layer earth model is employed.
b) Ground rods are represented.
c) The cable configurations are explicitly modeled.
d) Source substation sequence impedances are represented.

e) Source substation grounding system is explicitly modeled.

f) Induction phenomena between overhead feeder lines as well as between cable conductor and shield are taken into consideration.

Due to the amount of data presented the report is organized into two volumes. Volume I provides the background theory, an outline of the approach used and documentation of the computer program. Volume II is the handbook. It contains a detailed users guide and the data.

Section I.2

PROBLEM DEFINITION AND SOLUTION TECHNIQUES

The purpose of this section of the report is to define in general terms the problem of calculating step and touch potentials, the approach taken and the nature of the results generated. A discussion of the parameters of the problem and their impact on potential is given. Specific details of the solution procedure and attendant computer program are given in the Appendices.

2.1 PROBLEM DESCRIPTION

The general problem addressed in this report is the estimation by computer simulat ion of touch and step potentials in the vicinity of a faulted underground cable system. These potentials depend on a variety of factors such as:

- fault type and location
- earth conductivities
- cable burial depth
- cable parameters
- characteristics of the source network
- cable and grounding system configuration.

In view of the many parameters involved, the most difficult task in generating applicable data is that of reducing the problem to its essential elements so that a manageable amount of data will suffice. The general approach that has been taken to this has been to carefully analyze the sensitivities of the step and touch potentials to the various parameters and then segment the problem into two elements. Computer simulated results comprise one element, with the other element derived from known parameters of the system in question. Specifically, a set of computer data is generated which depends basically on cable type and soil composition. The results are displayed on curves in terms of step and touch potentials normalized to at-fault voltage. For each curve is a set of impedance data reflecting the earth conductive path. These impedance data together with impedances derived from the specific circuit in question enable computation of the un-normalized, at-fault voltage and the step and touch potentials. The rationale for this approach is discussed in the following subsection.

2.2 SYSTEM MODEL DESCRIPTION

Figure 2.1 shows the general network configuration employed in this study. A length of underground cable is supplied from an overhead transmission line from a substation. Ground rods are connected to the cable neutral at specified intervals. A simple substation ground grid is assumed and a two layer earth model is employed. Only the specific cable in question is represented directly in the model. Cables or other buried conductors in the vicinity of the specified cable are not included. The imposition of fixed network configuration and absence of adjacent buried conductors are necessary simplifications to reduce the amount of data to a manageable amount. Subsequent discussion will illustrate how results achieved with the model of Figure 2.1 can be extended.

The physical circuit description of Figure 2.1 can be represented by the equivalent electrical circuit shown in Figure 2.2. In this figure, the circuit is segmented into the earth return circuit and the electrical supply/cable circuit. If a fault between cable and sheath is assumed to exist at some point on the cable, a portion of the fault current will return to the source through the sheath and a portion will flow in the earth circuit. The current division will depend on cable type, system grounding and soil conductivities.

Viewed from point of fault, the circuit of Figure 2.2 can be reduced to the simpler lumped parameter equivalent circuit of Figure 2.3. The impedances shown are equivalent impedances from point of fault to remote ground, from substation neutral to remote ground and the transfer impedance from point of fault to the substation ground. This simplified circuit, with properly designated parameters, can be used to compute the at-fault voltage on the cable. That is, given the source voltage, the feeder circuit impedances and the equivalent earth impedances, the voltage at point of fault can be determined. The equivalent earth impedances depend on cable type, grounding, and soil resistivities and are determined by computer simulation.

2.3 OUTLINE OF COMPUTATIONAL PROCEDURE

The computer program which has been implemented to support this study basically solves the equations required to model the circuit of Figure 2.1. The model of the circuit comprises two essential elements; the earth conductive circuit and the connected network elements. The computer solution is correspondingly conducted in two parts. Appendices I.A and I.B describe in detail the equations used and the solution techniques employed. This section serves to outline the approach and methods.

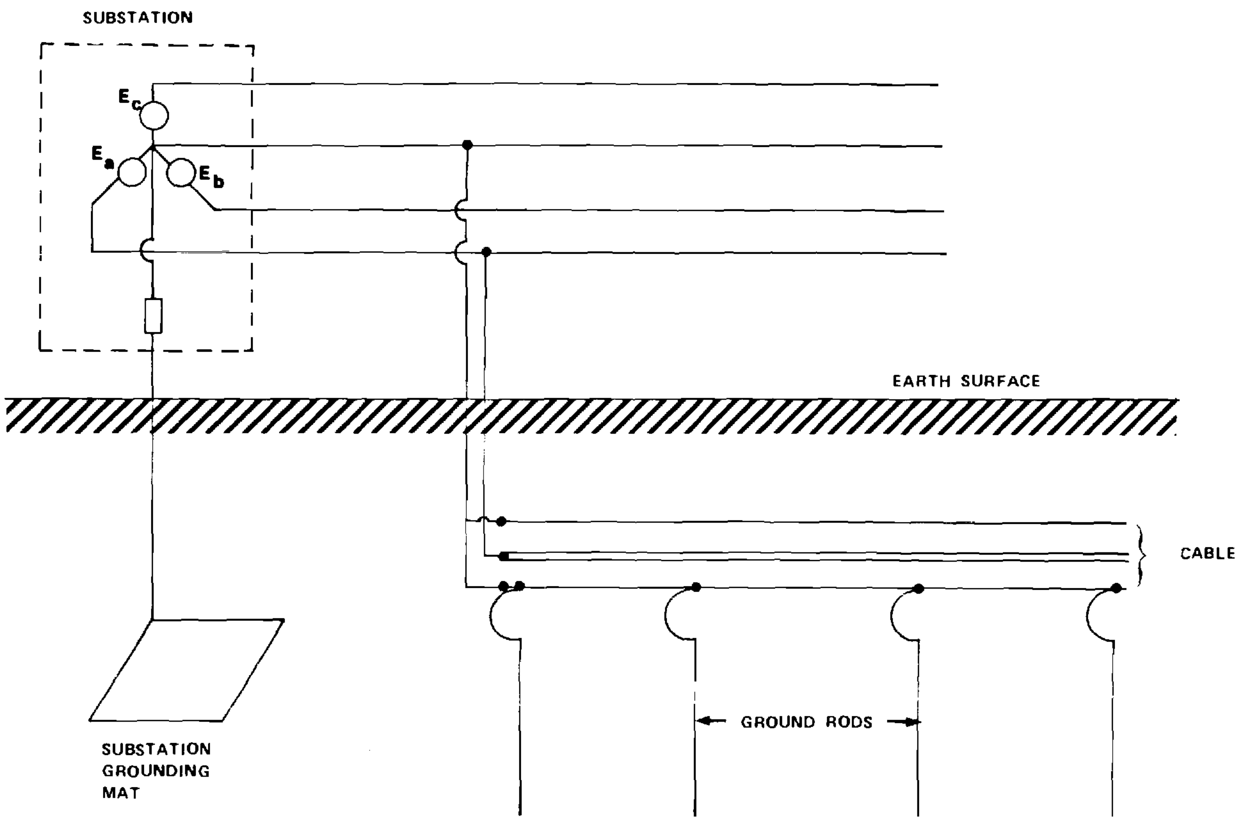


FIGURE 2.1 URD CABLE SYSTEM

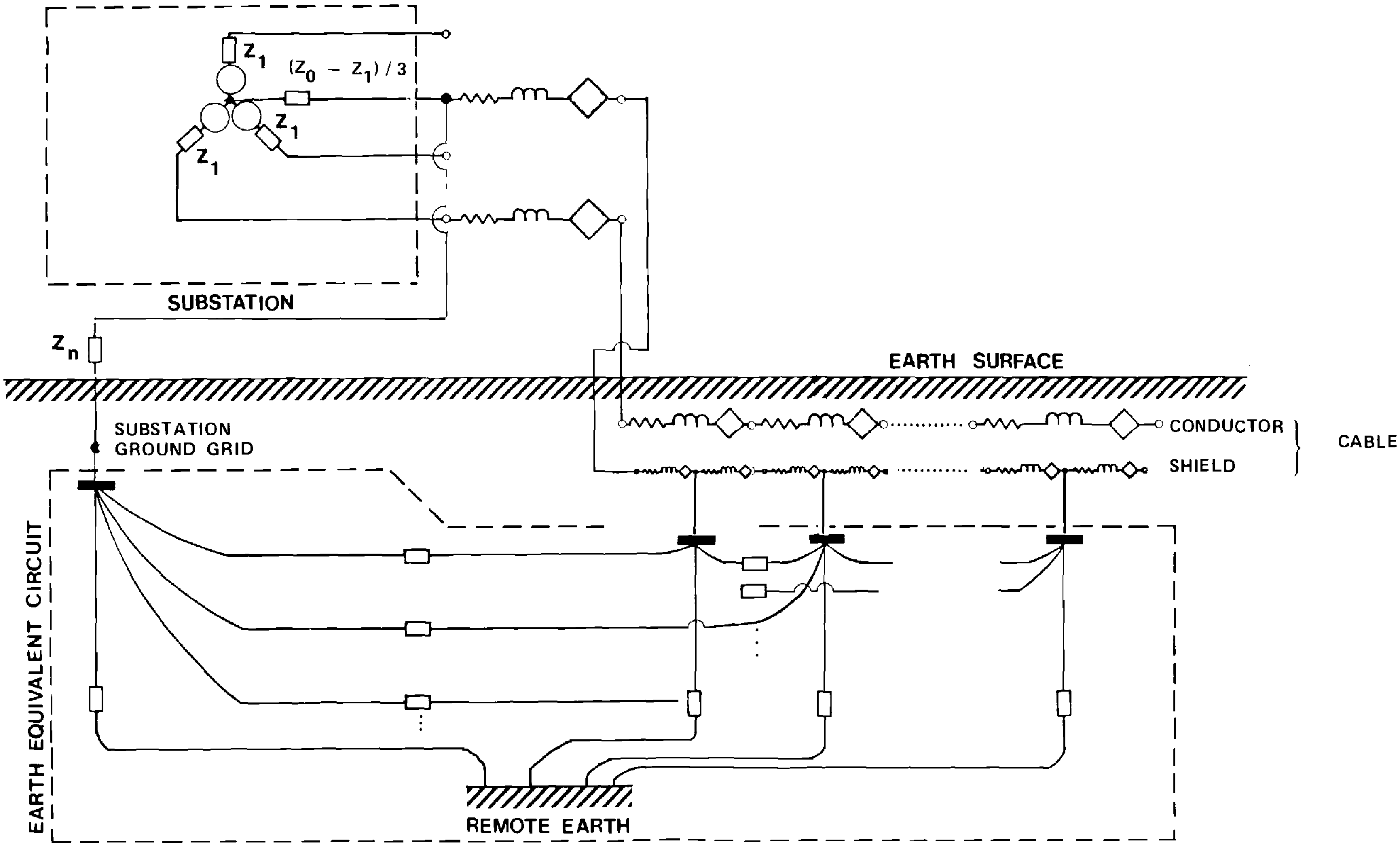


FIGURE 2.2 EQUIVALENT CIRCUIT REPRESENTATION OF SUBSTATION, OVERHEAD LINE, SUBSTATION GROUND, AND EARTH.

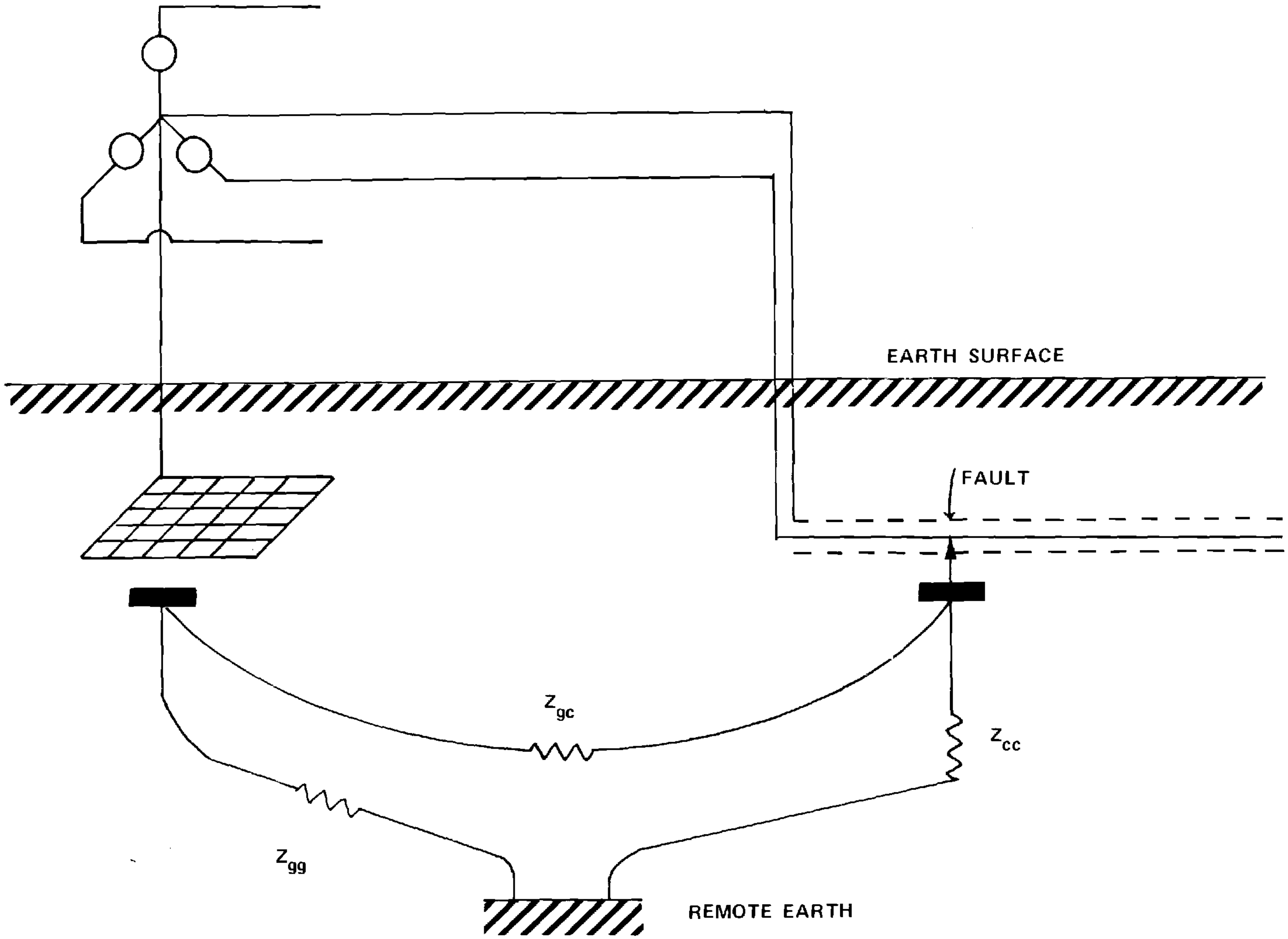


FIGURE 2.3 SIMPLIFIED EQUIVALENT CIRCUIT FOR EARTH RETURN

The first element of the solution procedure has to do with the earth conductive path. The result of this calculation is the determination of the equivalent resistances associated with this part. The method is based upon solution of Laplace's equation

where V(x,y,z) is a scalar potential function. This equation defines the potential and associated current flow in conducting media subject to boundary conditions resulting from media discontinuities or embedded conductors.

The solution to Laplace's equation consists of considering a set of small conducting segments embedded in two layer earth media. Using a numerical solution technique, a relation between the voltage on each segment and at each point in the medium resulting from current leaving all segments is derived. Using this result, an impedance matrix is computed which defines the equivalent impedance elements associated with Figure 2.2. This set of impedances is the main result obtained from the Laplace solution. These impedances are then employed in a composite model to obtain the complete solution.

The composite model defining the current and voltage relationships associated with Figure 2.2 for specific cases is obtained by employing a modified nodal analysis technique. This method is described in detail in Appendix I.B. In this approach, mutual coupling between phases of the overhead section and/or cable conductors and shield is represented using current dependent voltage sources. Then Kirchoff's current equations are written for each node and voltage equations written for each branch containing a current dependent voltage source. This results in a set of simultaneous equations whose solution yields the voltages and currents at every point in the network.

The above general procedure has been implemented in a computer program and has been utilized to plot touch and step potentials on the earth surface above the URD cable. Appendices II.A and II.B include the simulation results. Specifically, touch and step potentials are plotted for various cases in three regions of the earth surface:

- just above source end of cable
- just above fault location of cable
- just above cable end.

A sample plot is shown in Fig. 2.4. All plotted potentials are normalized with respect to at-fault voltage. Equivalent earth impedances are given in ohms. For

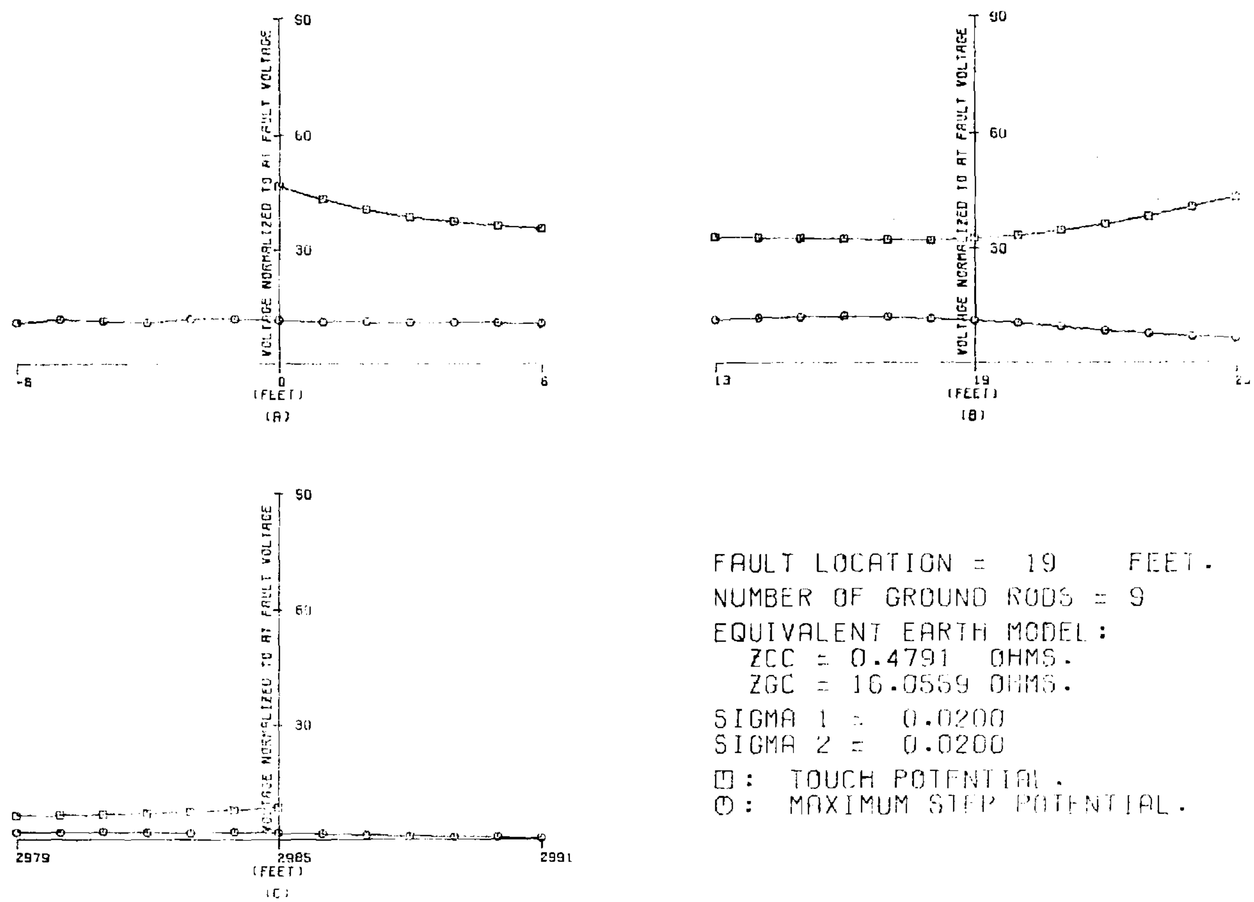


FIGURE 2.4 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

a specific situation, impedance data for the feeder and cable together with the earth impedance enable calculation of the magnitude of the expected at-fault voltage. Magnitudes of step and touch voltage may then be determined from the plots.

In general, the potential at any point in earth can be determined by the program. In particular, potential distribution on the earth surface may be of interest. Figures 2.5, 2.6, and 2.7 illustrate the distribution of potentials on the earth surface near the source end of the cable, near the fault and near the end of the cable respectively. The cable used for these curves has attached grounds at points centered on the closed contours. Higher surface potentials occur near points of ground rod attachment.

2.4 DISCUSSION OF PROBLEM PARAMETERS

The various parameters which effect the step and touch potentials are to be considered in order to provide some insight into potential variations with parameters. A qualitative discussion is followed by a quantitative analysis of specific parameters.

For purposes of this work, the touch and step potentials are defined as follows:

Touch potential at point x along the cable length is the potential difference between the cable neutral at point x and the earth surface immediately above x.

Step potential at point x along the cable length is the maximum potential difference between two points on the earth surface separated by three feet in the vicinity of point x. One of the two points is constrained to lie on a line six feet in length centered above x and directed perpendicular to the cable.

Generally speaking, the voltage at points on the earth surface located just above the buried cable develops a profile similar to the voltage profile of the cable shield. This similarity weakens as the cable burial depth increases. The maximum voltage gradients on the earth surface occur in a small region above the buried cable, but not necessarily directly above the buried cable. Also maximum step potentials occur in a direction not necessarily perpendicular to the axis of the cable. For this reason, the definition of step potentials given above is employed. For every point x along the cable, surface potential differences are computed for all three foot steps from a line on the surface perpendicular to the cable six feet in length, centered at x. These data are then searched to determine the maximum.

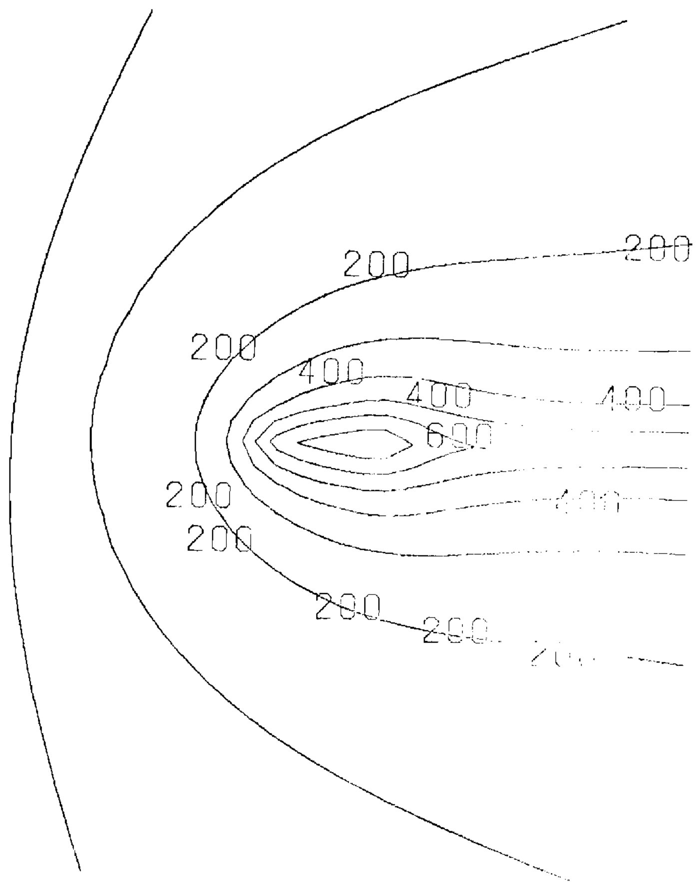


FIGURE 2.5 EQUIPOTENTIAL CURVES ON EARTH SURFACE NEAR SOURCE END OF CABLE.

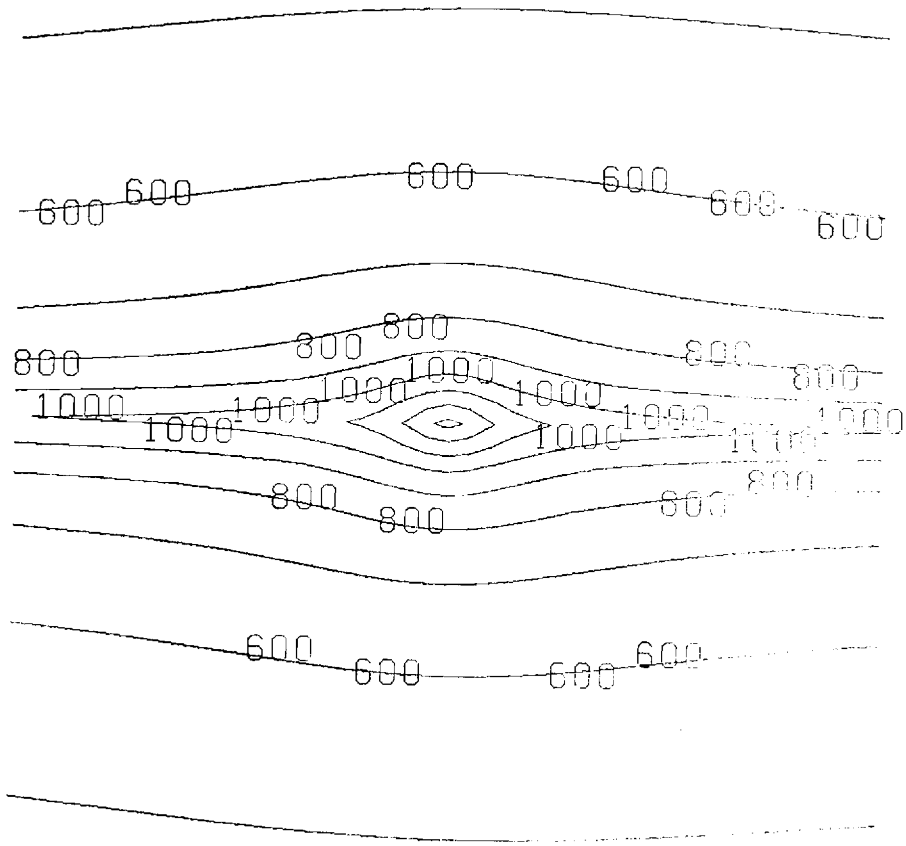


FIGURE 2.6 EQUIPOTENTIAL CURVES ON EARTH SURFACE NEAR FAULT.

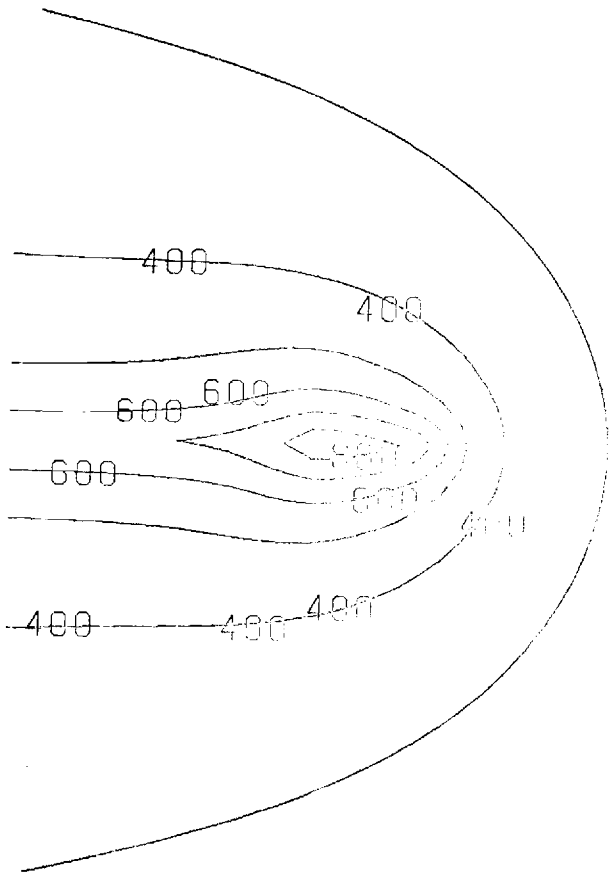


FIGURE 2.7 EQUIPOTENTIAL CURVES ON EARTH SURFACE NEAR END OF CABLE.

The primary determinants of the earth surface potentials are the magnitude and distribution of earth currents. The earth currents are influenced by the voltage rise of the substation ground and the buried cable shield. These electric currents will flow from the outer surface of the buried cable, through the earth into the substation grounding mat. In general, for a given cable, the earth current magnitudes will be inversely proportional to soil resistivity. Additionally, the jacket type determines the amount of earth current. An insulating jacket presents a high resistance to the flow of earth currents from the cable shield into earth. A semiconducting jacket resistances are variable, depending on jacket material resistivity. For commonly used semiconducting jacket resistivity, the earth current limiting effect of the jacket is negligible. Thus, for the purposes of computing earth currents, the presence of a semiconducting jacket has negligible effect.

Several factors in addition to cable type and soil resistivity influence the earth current flow. The cable shield is not at constant voltage during abnormal or normal conditions. Phase shift effects and voltage drop due to fault current through the cable shield result in a certain voltage profile along the cable shield. This voltage profile is determined by a large number of parameters, involving the external circuit and the soil properties. These factors may result in situations where electric current emanating from the surface of the cable return partly to the substation ground and partly to the cable shield at another point. This situation is illustrated in Figure 2.8.

Since earth leakage currents depend on cable shield voltage profile which varies along the length of the cable, it is clear that the location of the fault affects the earth currents. Fault location affects short circuit currents flowing through the cable shield and thus the voltage drop across the shield. Thus the location of the fault impacts considerably on the voltage profile of the cable shield. If the cable is bare or jacketed with semiconducting jacket, the earth leakage current will be directly related to the shield voltage profile. If the cable has insulating jacket, the effect of cable shield voltage profile on earth leakage current is not significant.

Another important factor affecting earth leakage currents is the configuration and condition of the neutral system. If the neutral is continuous from substation ground to the cable shield and in addition, the cable shield is intact (not corroded), most of the fault current circulates in the phase conductors and the neutral conductors because these paths present relatively low impedance to the flow of currents as compared to the resistance of the earth path. If, however,

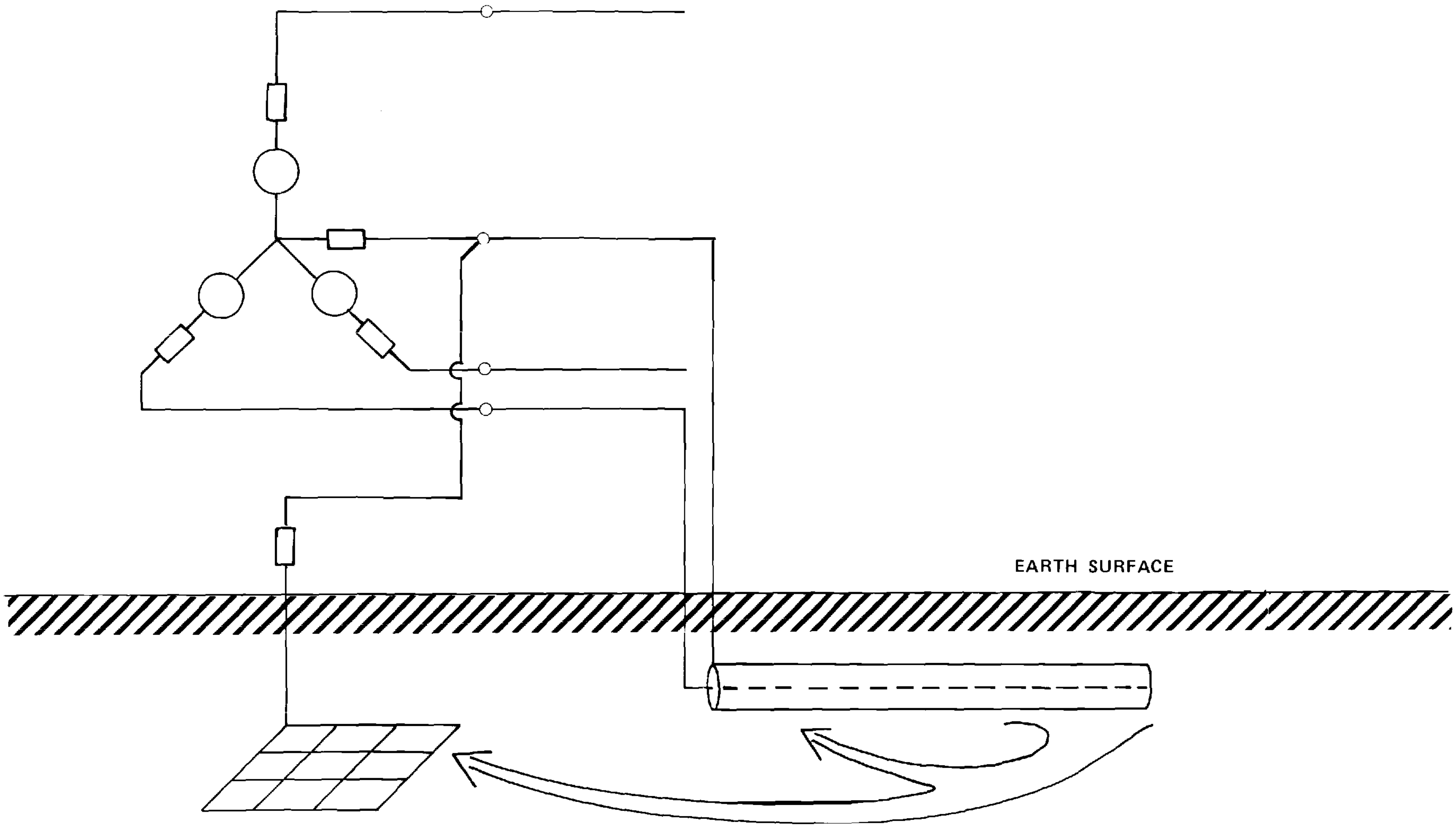


FIGURE 2.8 POSSIBLE PATH OF FLOW OF EARTH CURRENTS

there is a discontinuity in the neutral system (lack of overhead ground wire, or corroded cable shield), all the fault current has to return through the earth path. In this case earth currents are considerably higher. This situation also results in considerably higher earth voltages.

Another important aspect of the earth currents involves the relationship to the cable voltage at point of fault. That is, for a given cable, the at-fault voltage is dependent on the division of fault current between the earth returns paths and the cable shield. Furthermore, over a wide range of parameters, it can be shown that the earth surface potentials are essentially proportional to the at-fault voltage. Consequently, at-fault voltages determined for one set of parameters may be extrapolated to another set if the relationship of the parameter to at-fault voltage is defined. This fact has lead in this report to the normalization of computed step and touch potentials to the at-fault voltage.

For a specific fault point the relationship of the at-fault voltage to the earth currents and the sheath current can be represented by the reduced equivalent circuit of Figure 2.3. It should be noted that the equivalent impedance Z_{cc}, and Z_{gc}, shown are determined by computer and represent the relationship between at-fault voltage and earth currents, for given cable and soil parameters. Once these impedances are determined, the associated step and touch potentials, normalized to the at-fault voltage for the specified condition, can be applied to other conditions, thus extending the range of application of these results.

An analysis of Figure 2.3 provides considerable insight into the determinants of at-fault voltage. Referring to the figure it may be seen that the at-fault voltage depends both on the external network and the equivalent circuit of the earth (Z_{gg}, Z_{gc}, Z_{cc}). The external circuit includes the substation, the feeder circuit as well as the conductor and shield of the cable. The external circuit can be described in terms of the positive and zero sequence impedances of the electrical circuit between the substation and the point of fault.

The effects of the earth circuit are represented by the impedances Z_{cc}, Z_{gc}, Z_{gg}. Impedance Z_{cc} is the equivalent impedance from the outer surface of the cable conductor to remote earth, referred to the point of fault. As the length of the cable increases Z_{cc} will decrease due to increased surface area in contact with earth. (For insulated cable, this effect is, of course, small due to the high resistance presented by the jacket). With other factors fixed, the at-fault voltage is proportional to Z_{cc}.

The impedance Z_{gg} represents the equivalent impedance of the substation ground mat. This impedance can be determined for a given mat by application of IEEE Std-80 or by means of recently developed computerized procedures. The substation ground acts as a current limiting impedance for the earth current. Consequently, the at-fault voltage on the cable decreases with increasing Z_{gg}.

The impedance Z_{gc} is a transfer impedance between the substation ground and the cable. It also represents a limiting impedance to earth current and thus effects at-fault voltage in a manner similar to Z_{gg}.

2.5 PARAMETRIC EFFECTS

A relatively large number of parameters impact on the level of touch and step potentials resulting from underground cable faults. In preceding paragraphs, a qualitative discussion of the most important parameters as well as their effect on touch step voltages was given. In this section this discussion is extended in a quantitative way. The objective is to provide more insight into the problem of computing touch and step potentials.

a) External Circuit parameters

The external circuit parameters greatly effect the at-fault voltage. The circuit parameters are defined by the following quantities:

- positive sequence impedance at substation bus
- zero sequence impedance at substation bus
- positive sequence impedance of the overhead line
- zero sequence impedance of the overhead line
- cable impedance (between source end and fault)
- cable neutral size.

Roughly speaking, the external circuit acts as a voltage divider which defines the at-fault voltage. The voltage divided is the substation secondary nominal voltage. The division ratio is determined by the above defined parameters. The following parameters <u>decrease</u> the division ratio if they are <u>increased</u>:

- positive sequence impedance at substation secondary bus
- zero sequence impedance at substation secondary bus
- positive sequence impedance of the overhead line
- cable impedance (between source end and fault)

The following parameters <u>increase</u> the division ratio if they are <u>increased</u>:

- zero sequence impedance of overhead line

- per unit length impedance of cable neutral.

Figure 2.9 illustrates quantitatively the effect of the substation secondary bus positive sequence impedance on the level of the at-fault voltage. All other parameters are assumed to be constant. The same impact results from by the positive sequence impedance of the overhead line and cable impedance between source end and fault.

Figure 2.10 illustrates the effect of the substation zero sequence impedance on the level of at-fault voltage. As Z_0 increases, the at-fault voltage decreases. Again all other parameters are fixed at constant value. An opposite effect is incurred by the zero sequence impedance of the overhead line and the per unit length resistance of cable neutral. Thus a 1/3 neutral cable will yield higher at-fault voltage than a full neutral cable, other things being equal. The level of increase will depend on external circuit zero sequence impedance.

Finally, Figure 2.11 illustrates the dependence of at-fault voltage on overhead line length. The at-fault voltage is insensitive to overhead line length. The reason is that both positive and zero sequence impedances of the line increase commensurately with length. The effect of one is compensated by the effect of the other. Another reason for which the at-fault voltage is insensitive to overhead line length is that the impedance of the line is small compared to the impedance of the substation.

b) Cable parameters

Two of the cable parameters, namely cable conductor impedance and neutral resistance per unit length, are included in the external circuit parameters and were discussed in the preceding section. In this section the effects of jacket parameters, and presence/lack of ground rods are discussed. No practical difference between a bare cable and a cable jacketed with semiconducting jacket of conductivity in the range 1 ℧/m to 10^{-3} ℧/m exists. Also, the impact on surface potentials of outside cable diameter is practically negligible. In general, bare cables or jacketed cables with semiconducting jacket, with or without ground rods, present a low resistance to remote earth. This leads to low at-fault voltages. A long cable of this type may present considerable lower resistance to remote earth than the substation ground equivalent resistance. This situation will lead to high voltage elevation of substation neutral, and

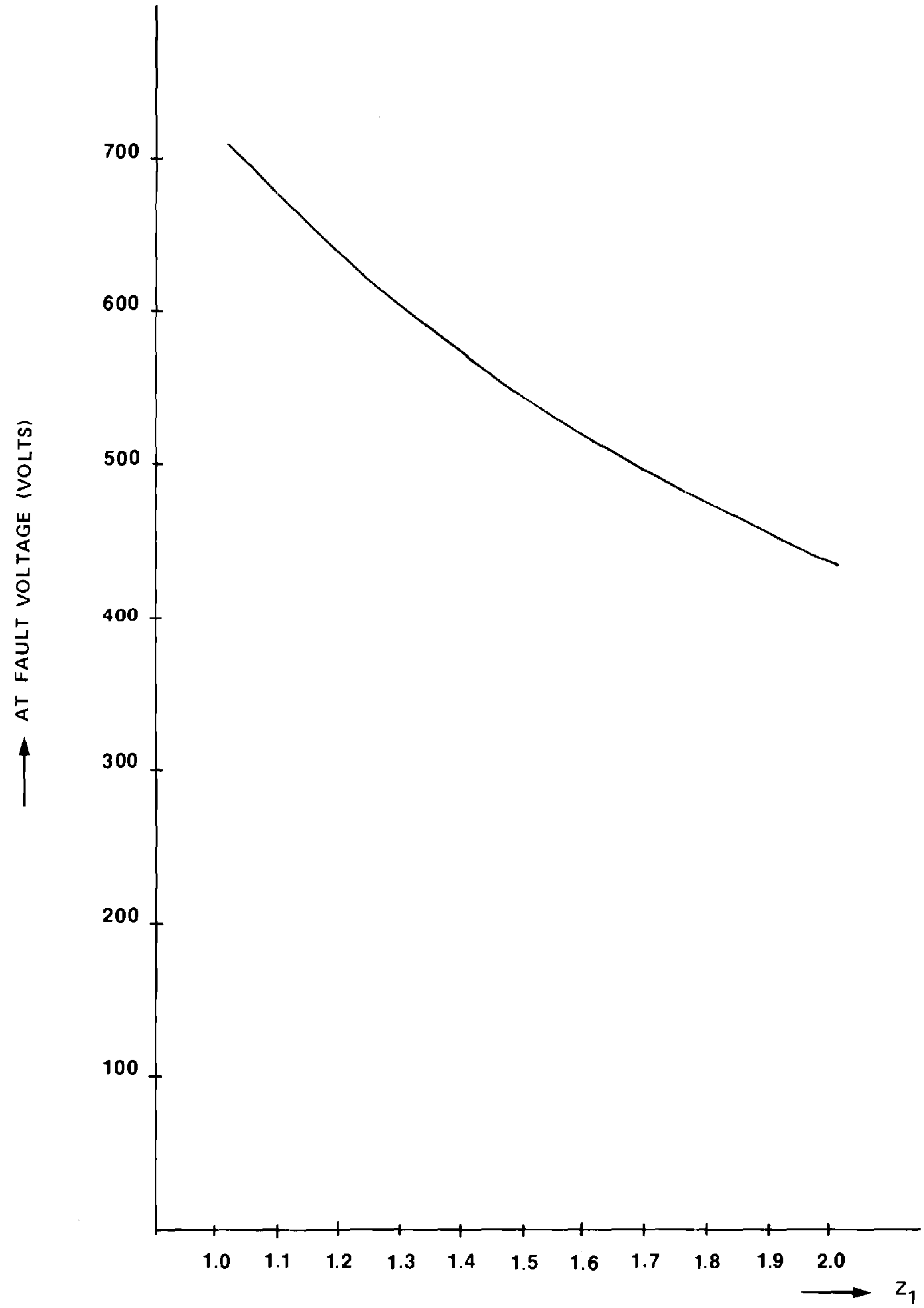


FIGURE 2.9 AT FAULT VOLTAGE AS A FUNCTION OF THE SUBSTATION POSITIVE SEQUENCE IMPEDANCE.

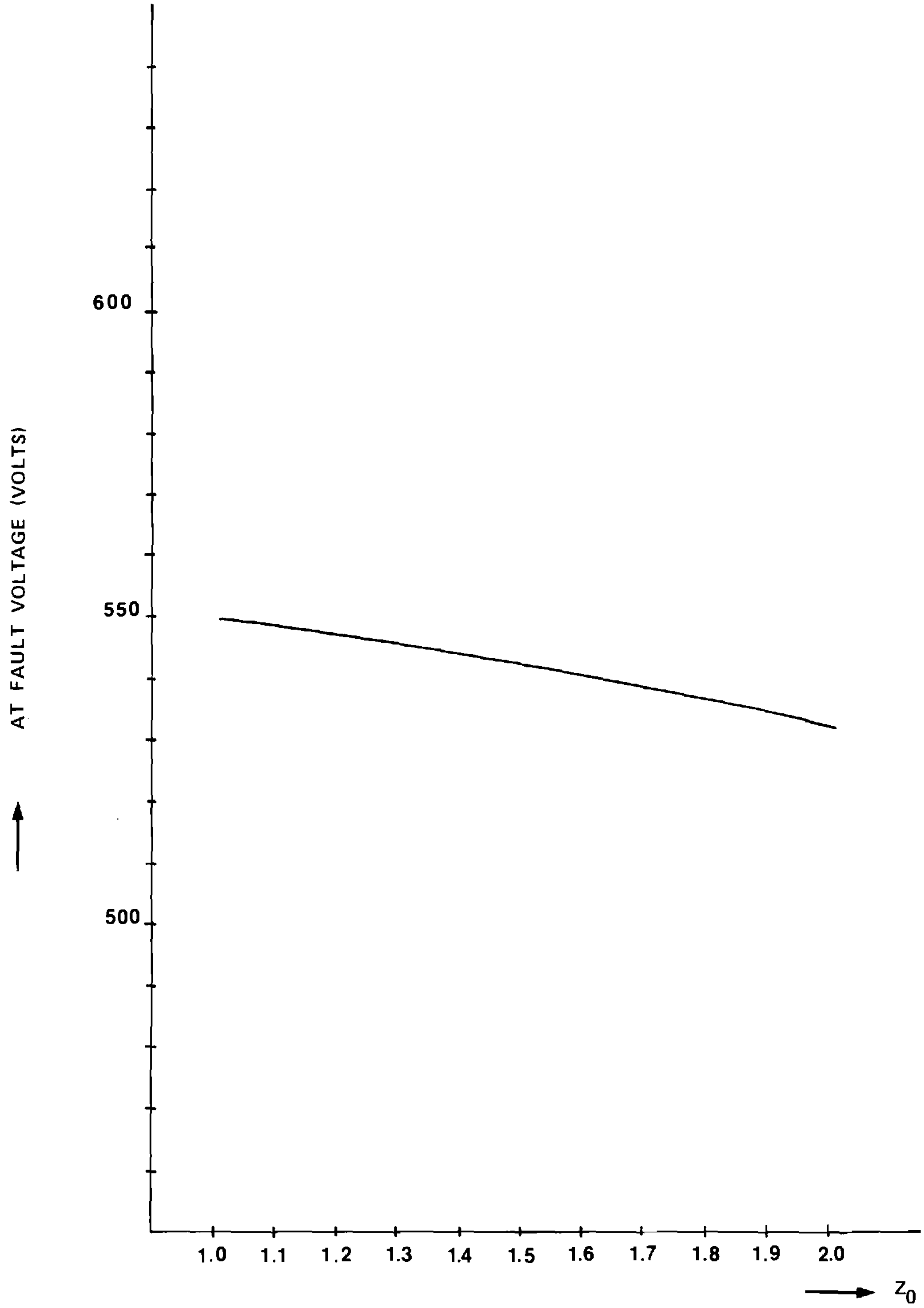


FIGURE 2.10 AT FAULT VOLTAGE AS A FUNCTION OF THE SUBSTATION ZERO SEQUENCE IMPEDANCE.

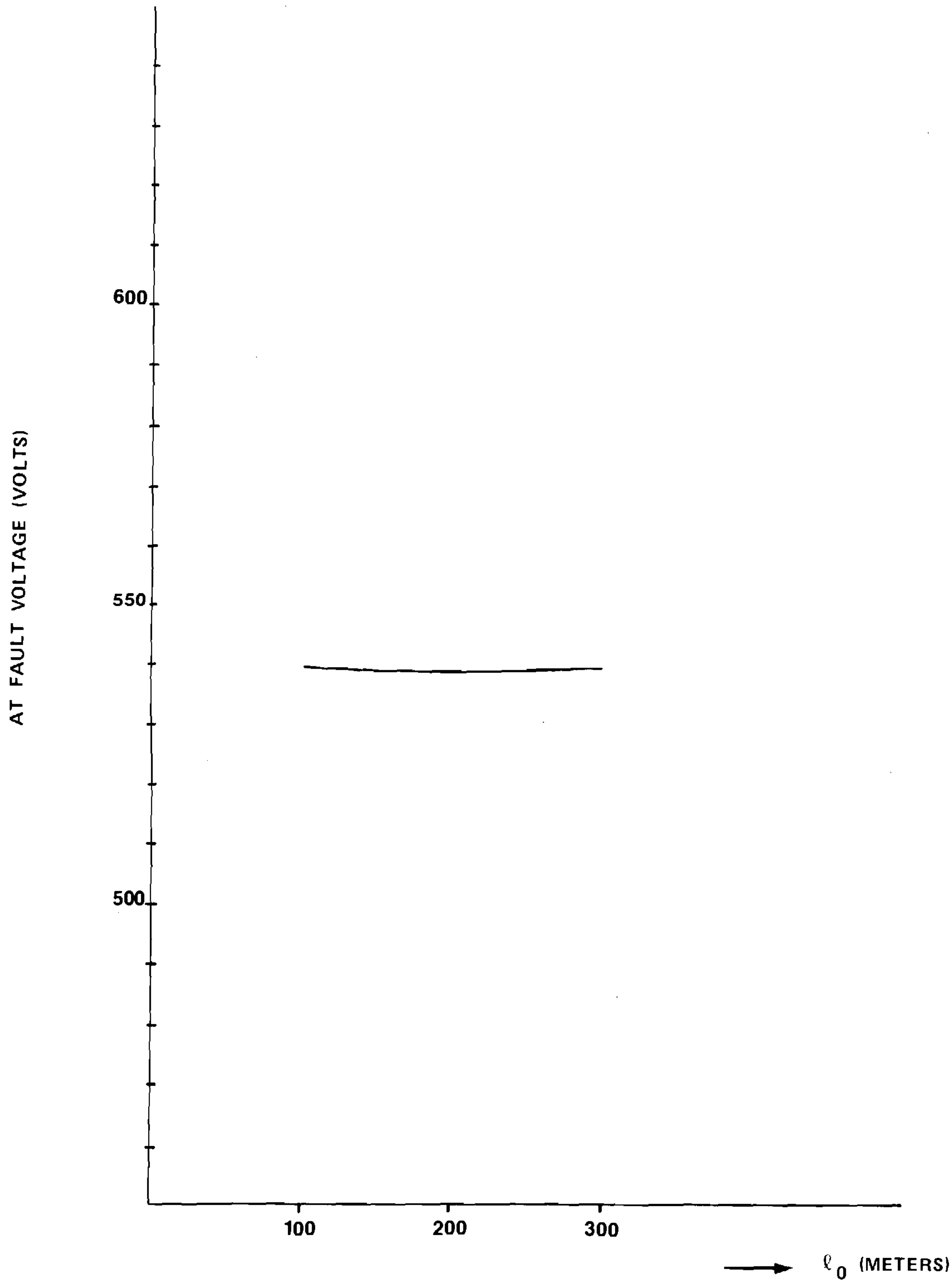


FIGURE 2.11 AT FAULT VOLTAGE AS A FUNCTION OF THE LENGTH OF THE OVERHEAD LINE.

substation grounding mat and high touch and step potentials in the vicinity of the substation.

Jacketed cable with insulating jacket and without ground rods are basically isolated from earth. Earth leakage current is very small. The at-fault voltage is exclusively determined by the circuit parameters. This situation leads to high touch voltages and very low step voltages along the length of the cable.

Insulating jacketed cable with ground rods behave anywhere between the above two extreme cases. The number of ground rods and their length have a profound impact. In general, earth leakage current and step voltages increase almost proportionally with the total length of ground rods. The at-fault voltage decreases almost inversely proportionally with the total length of ground rods.

Finally, Figure 2.12 illustrates the composite impact of cable parameters on at-fault voltage. All cables are assumed to be bare. The fact that the at-fault voltage is lower for large cables is mostly attributed to low neutral resistance per unit length.

c) Earth parameters

The earth is modeled as a two layer semi-infinite medium with the following parameters:

0 - 3' conductivity (σ_2) or resistivity (ρ_2)
3' - ∞ conductivity (σ_1) or resistivity (ρ_1)

The purpose of this section is to quantitatively discuss the impact of above parameters on touch and step voltage level.

It is noted that in the case of URD cable with insulating jacket and without ground rods, the touch and step voltages are insensitive to variations of σ_1, σ_2. Thus the discussion is confined to bare or semiconducting jacket cable with or without ground rods and insulating jacket cable with ground rods.

The parametric effect is best illustrated with Figures 2.13, 2.14, 2.15, and 2.16. The content of these figures may be summarized as follows:

Bare/Semiconducting Cable

1. The at-fault voltage slightly decreases as soil conductivity increases (or soil resistivity decreases).
2. Normalized touch and step voltages slightly increase as soil conductivity increases (or soil resistivity decreases).

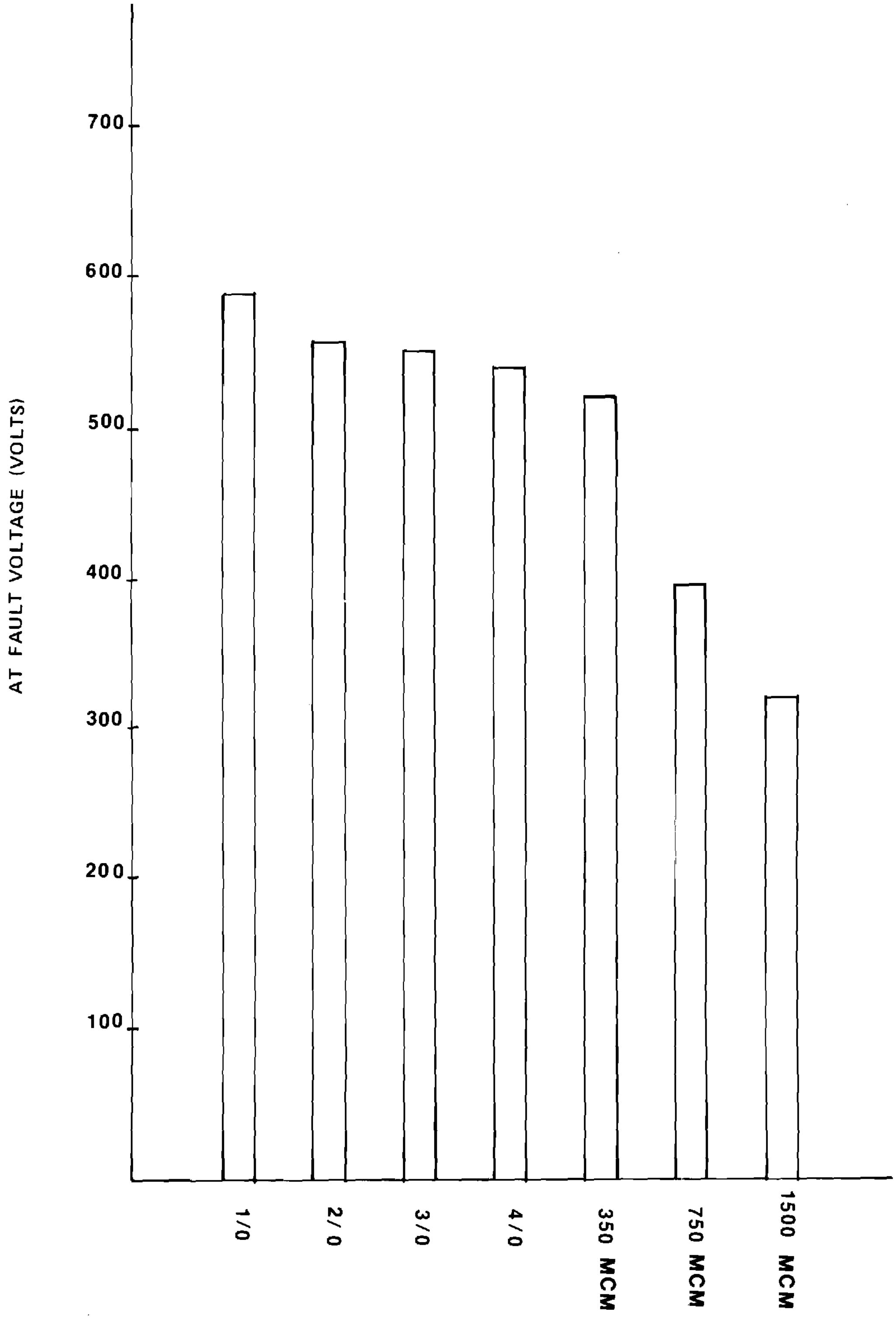


FIGURE 2.12 AT FAULT VOLTAGE FOR VARIOUS CABLE SIZES WITH FIXED FAULT LOCATION AND EXTERNAL CIRCUIT.

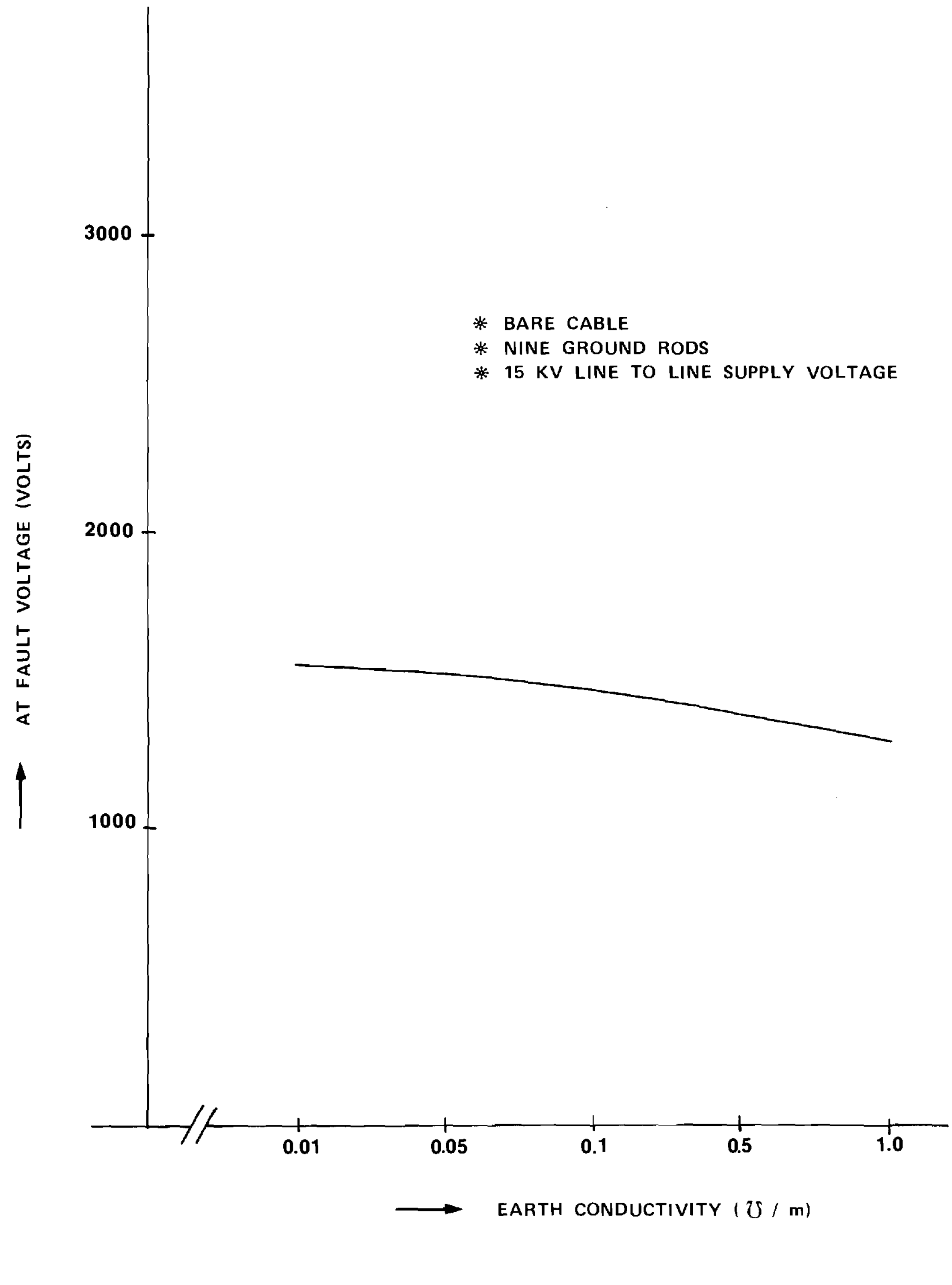


FIGURE 2.13 AT FAULT VOLTAGE AS A FUNCTION OF EARTH CONDUCTIVITY.

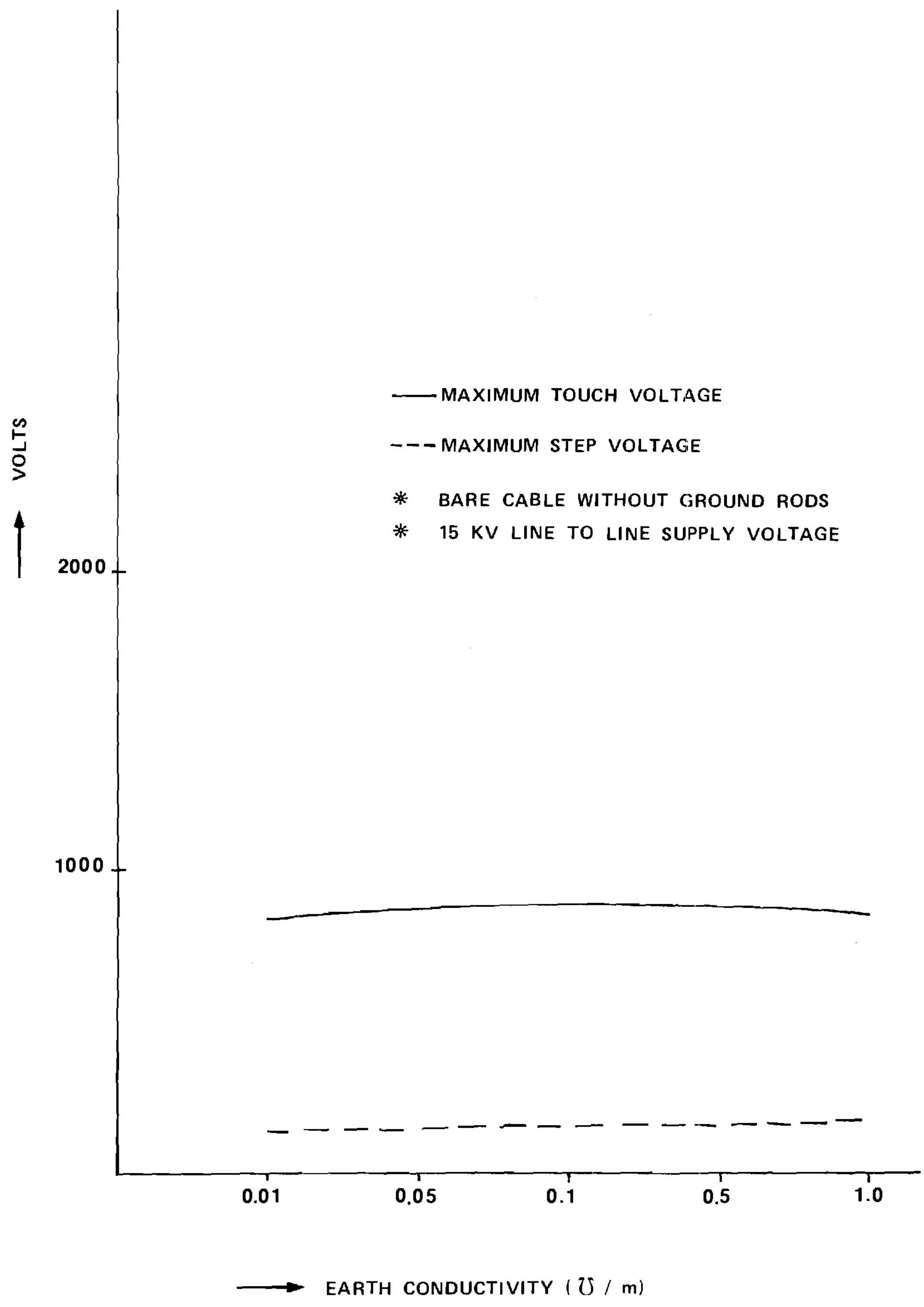


FIGURE 2.14 TOUCH AND STEP VOLTAGES AS A FUNCTION OF SOIL CONDUCTIVITY.

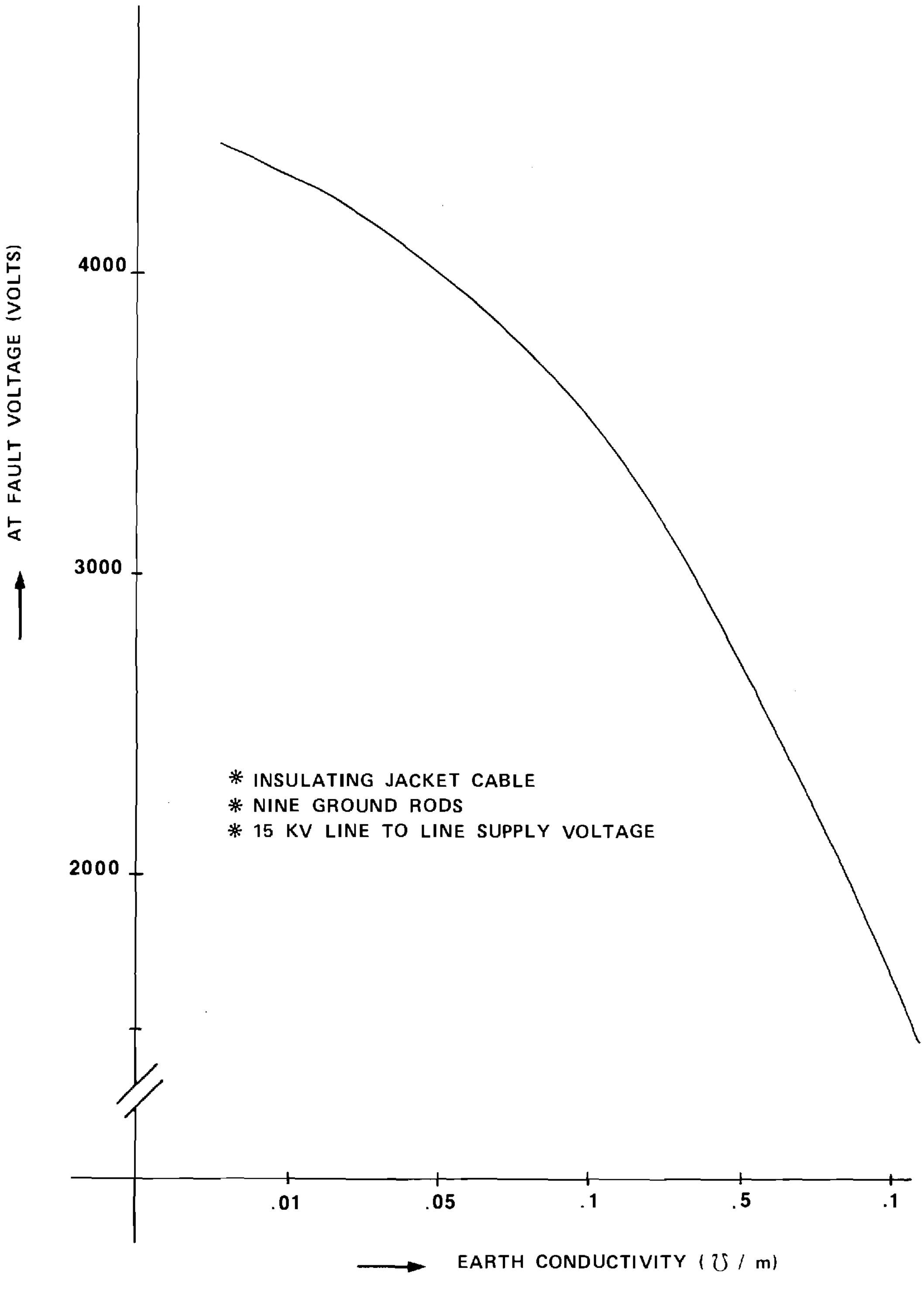


FIGURE 2.15 AT FAULT VOLTAGE AS A FUNCTION OF EARTH CONDUCTIVITY.

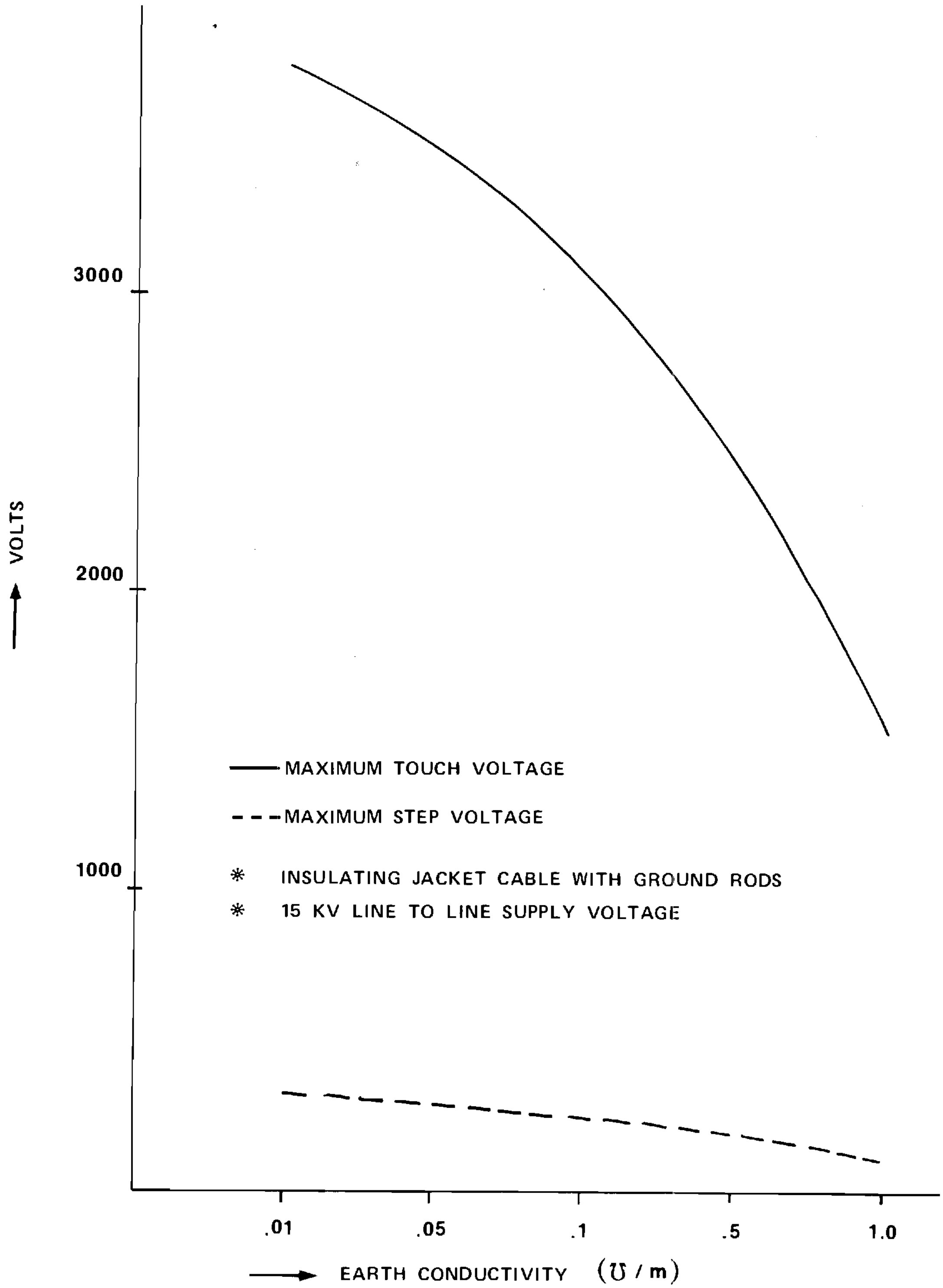


FIGURE 2.16 TOUCH AND STEP VOLTAGES AS A FUNCTION OF SOIL CONDUCTIVITY.

Cable with Insulating Jacket and Ground Rods

1. The at-fault voltage sharply decreases as soil conductivity increases (or soil resistivity decreases).
2. Above pattern is followed by the touch and step voltages.
3. Touch voltages are high as compared to touch voltages of bare/semiconducting cables.
4. Step voltages are very low.

d) Grounding configurations

Substation grounding configurations are defined by the associated equivalent resistance to remote earth. High resistance of the substation ground limits the earth currents and thus the at-fault voltage at the cable. Thus higher substation ground resistance will yield lower touch and step potentials around the cable. Figure 2.17 illustrates the impact of substation ground impedance Z_{gg} on at-fault voltage.

It should be emphasized that it is not desirable to increase the substation ground resistance in order to decrease touch and step potentials in the vicinity of the cable. This is so because the higher the impedance Z_{gg}, the higher the voltage elevation of the substation ground mat and thus higher touch and step potentials in the vicinity of the substation.

e) Fault location

The location of the fault impacts on the cable shield voltage profile, earth currents, at-fault voltage and touch and step voltages. The relationships involved are complex. In general, it has been observed that the maximum touch and step voltages increase as the fault location moves away from the source end of the cable. Figure 2.18 illustrates touch and step voltage variation as a function of fault location for an insulating jacket cable with ground rods. It is noted that the effect on step and touch potentials is less significant in bare or semiconducting jacketed cables.

f) Neutral system

In the preceding sections, it was assumed that there is continuous electrical connection between the faulted URD cable neutral and the substation neutral. In other words, the neutral system is intact. However, the handbook data are applicable to cases of missing overhead ground wire and/or corroded cable neutral.

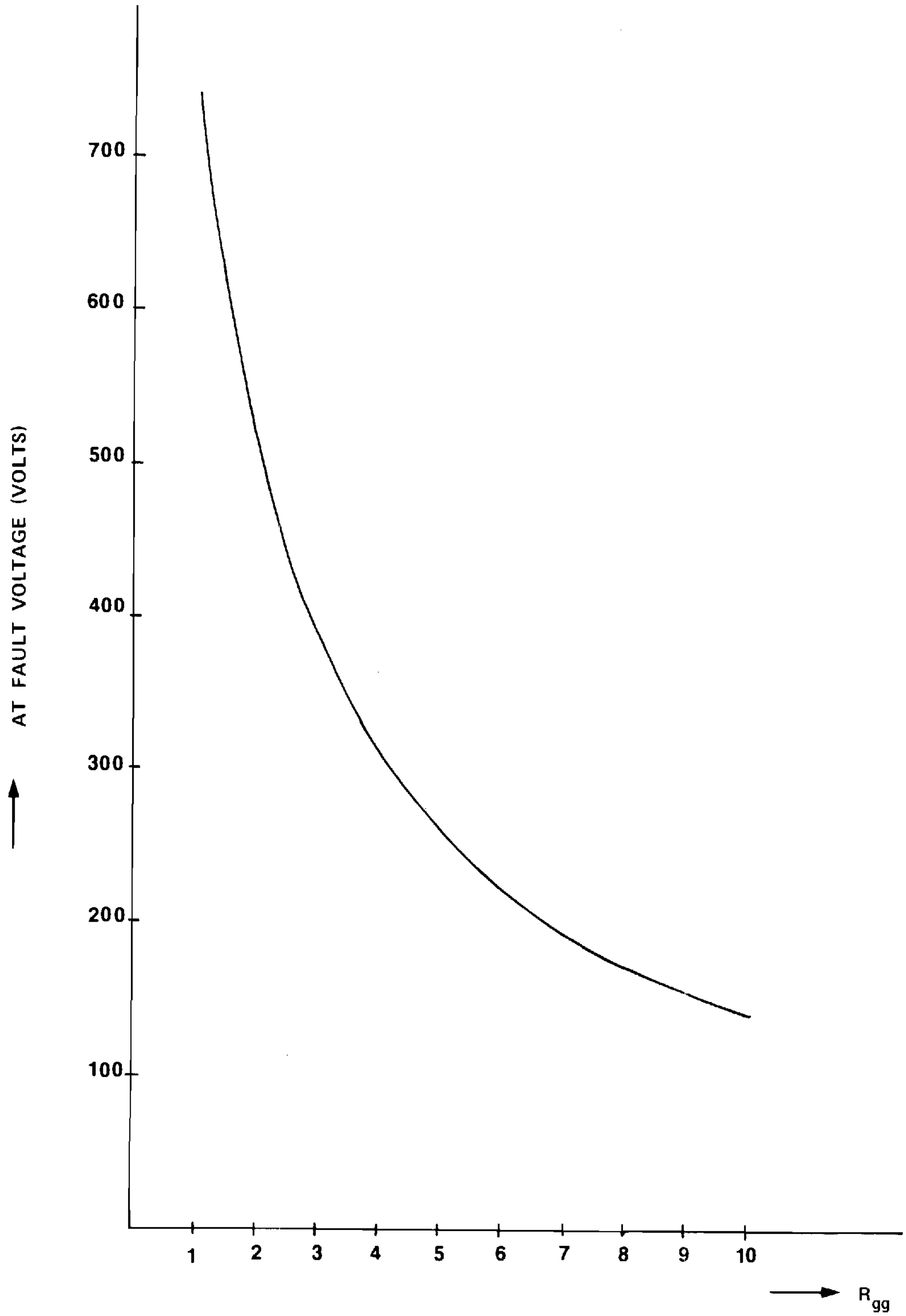


FIGURE 2.17 AT FAULT VOLTAGE AS A FUNCTION OF SUBSTATION GROUND RESISTANCE.

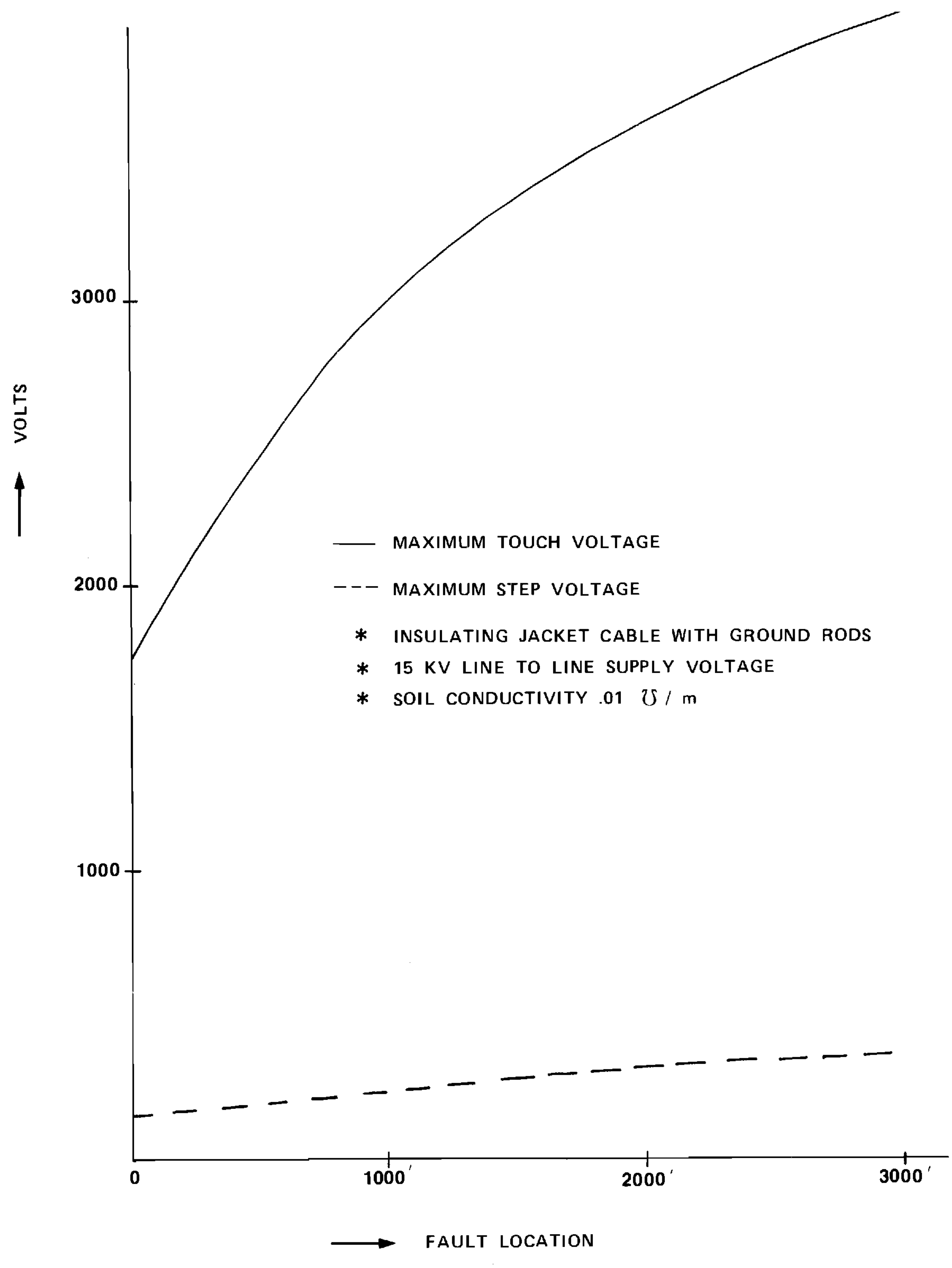


FIGURE 2.18 TOUCH AND STEP VOLTAGES AS A FUNCTION OF FAULT LOCATION.

When the neutral system is not continuous, the fault current has to return through the earth path. The situation results in considerably higher earth currents, higher at-fault voltage and higher touch and step voltages. This condition is the worst possible case in terms of touch and step voltages. As an illustration of this claim, Table 2.1 presents data for a bare 15 kV cable with continuous and non-continuous neutral system.

Figure 2.19 illustrates the distribution of normalized touch and step voltages for a bare cable, faulted at approximately 1500 feet from source end, without electrical connection to substation ground. Note that the distribution is similar to one of a system with continuous neutral and the fault located near the source end of the cable. The similarity is justified from the fact that the cable shield voltage profile is similar in both cases. For highly conductive soils, however, or very long cables, the above statement must be modified.

TABLE 2

TOUCH AND STEP VOLTAGES WITH CONTINUOUS AND NON–CONTINUOUS NEUTRAL SYSTEM.

	MAXIMUM TOUCH VOLTAGE	MAXIMUM STEP VOLTAGE
CONTINUOUS NEUTRAL SYSTEM	225 VOLTS	60 VOLTS
NON–CONTINUOUS NEUTRAL SYSTEM	693 VOLTS	184 VOLTS

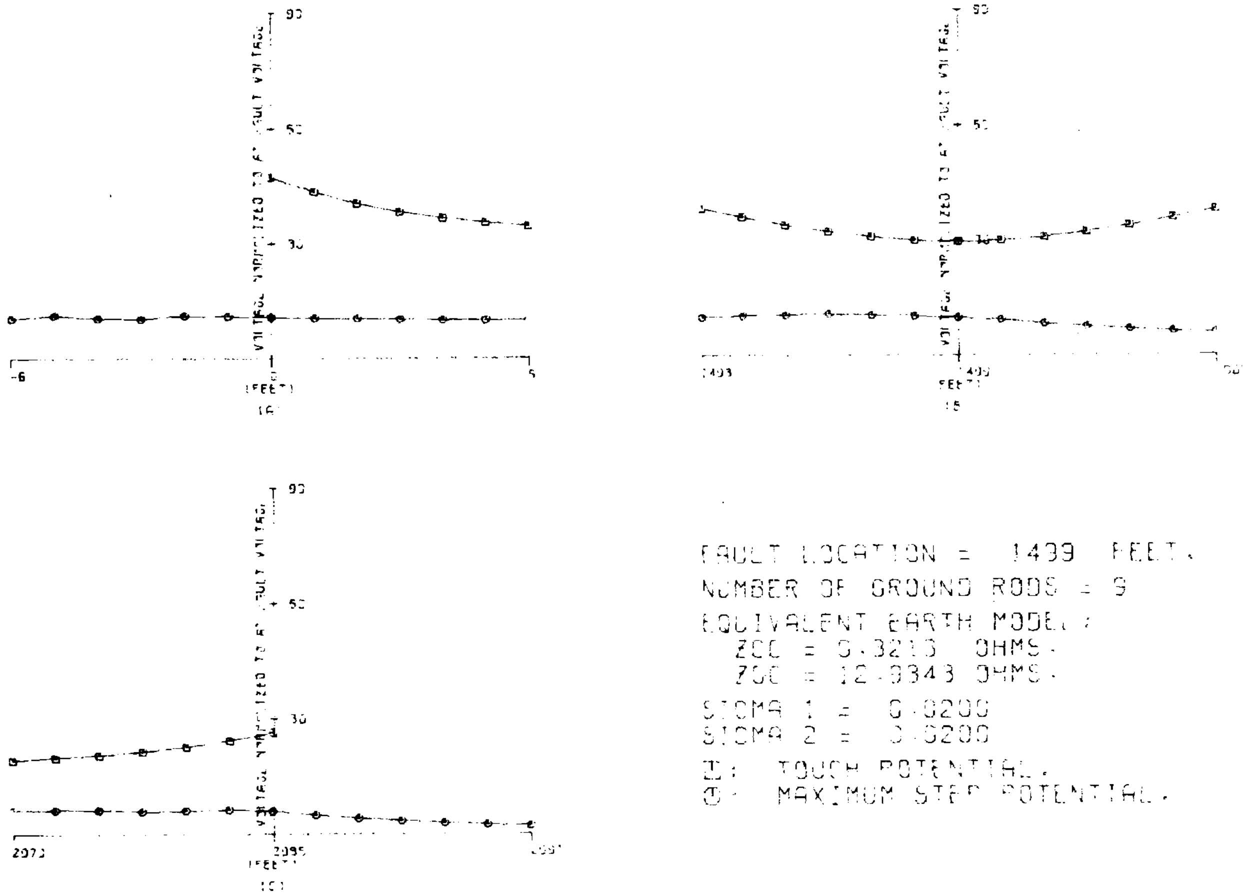


FIGURE 2.19 TOUCH AND STEP POTENTIALS:
A: NEAR SOURCE END OF CABLE
B: NEAR FAULT.
C: NEAR CABLE END.

Section I.3

DESCRIPTION OF THE COMPUTER PROGRAM

The developed computer program is segmented into two subprograms. The first subprogram, which bears the symbolic name BCAB1, accepts the parameter values of the problem, performs the segmentation of the URD cable system, generates all circuit equations, and conditions the data to be accepted by the second program. The second subprogram, symbolic name BCAB2, computes the earth equivalent circuit, solves the resulting network problem, computes the earth currents and from the earth currents touch and step potentials. Finally, touch and step potentials are plotted.

The input data required by the computer program are listed in Table 3.1. The standard output of the computer program is plots of touch and maximum step potentials at three regions of the URD cable: near the source end of the cable, near the fault, and near the end of the cable. A standard output is illustrated in Figure 3.1.

The underground cable system is represented with 67 earth embedded segments. The segmentation is performed in the first subprogram. The same subprogram generates the network equations in sparse form. Sparcity programming was necessary because of the size of the network problem. The generated data are stored in a temporary file. This file is then fed into the second subprogram. A flow chart of the first subprogram is shown in Figure 3.2.

The second subprogram, which is also sparcity coded, performs the actual computations. First the Z_{LAP} matrix is computed for the segmented underground cable system. At this point the equivalent circuit representation of the system and associated equations are complete. Next the circuit equations are solved. From the solution the earth currents are defined. Back substitution yields voltage level along the cable shield. Next, voltages at a selected grid of points on the earth surface are computed by employing the equations of Appendix I.A. From above voltages and voltage along the cable shield, touch and maximum step potentials are computed. Finally, touch and maximum step potentials are plotted. A flow chart of the second subprogram is illustrated in Figure 3.3.

Table 3.1

PROGRAM INPUTS

CABLE PARAMETERS

- outside diameter, d_o
- conductor resistance per mile, r_c
- shield resistance per mile, r_s
- conductor GMR, d_c
- shield average radius, c_ℓ
- jacket: conductivity and thickness, σ_J, t
- burial depth, d_b
- cable length, ℓ
- fault position, ℓ_f

SUBSTATION PARAMETERS

- substation ground resistance, R_s
- positive (negative) sequence impedance, Z_1
- zero-sequence impedance, Z_o
- supply voltage, E (line-neutral)

OVERHEAD FEEDER PARAMETERS

- phase conductor resistance per mile, r_p
- phase conductor GMR, d_p
- ground wire resistance per mile, r_g
- ground wire GMR, d_g
- GMD between phase conductor D
- average height, h
- feeder length, l_o

SOIL PARAMETERS

0 - 3' conductivity, σ_2

3' - infinity conductivity, σ_1

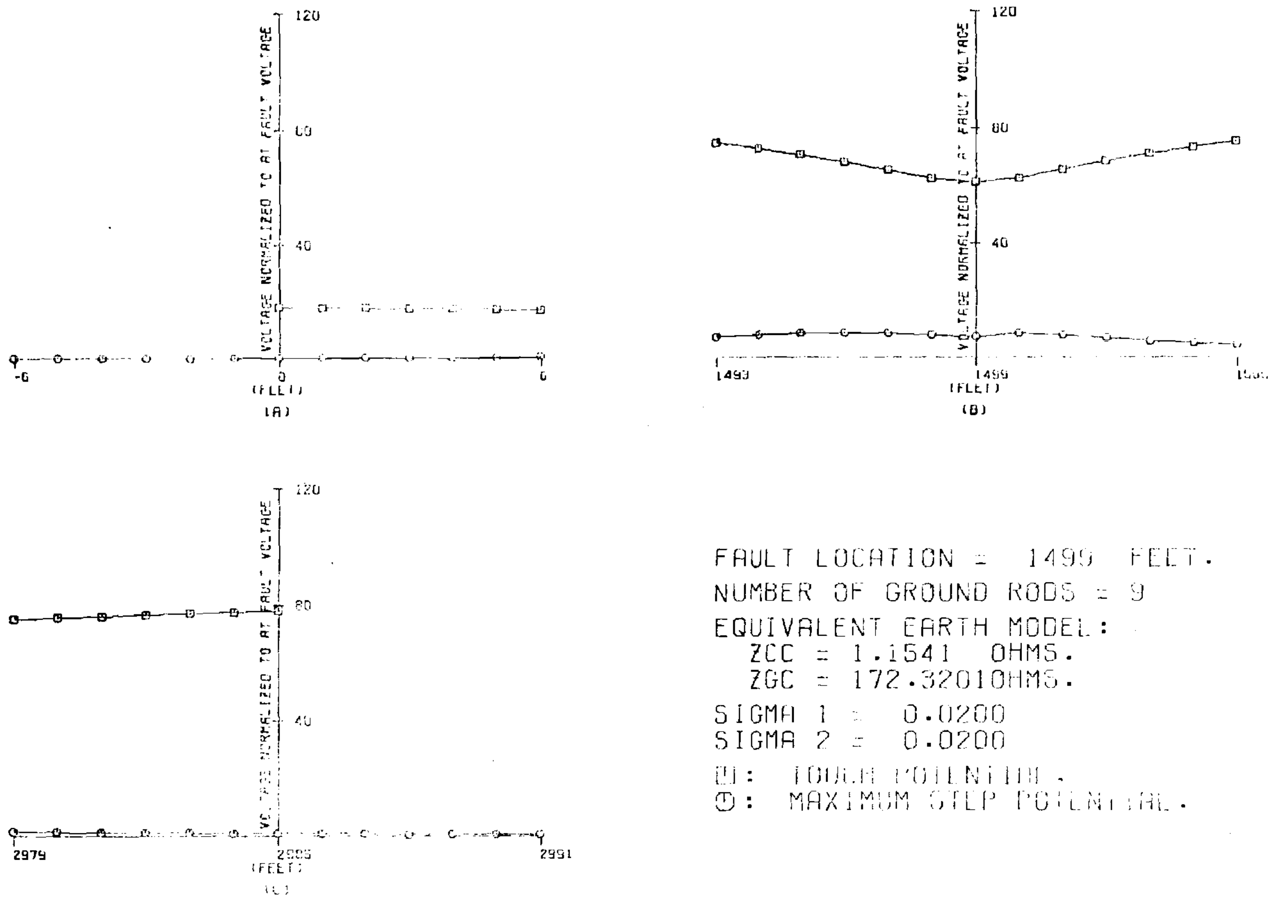


FIGURE 3.1 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

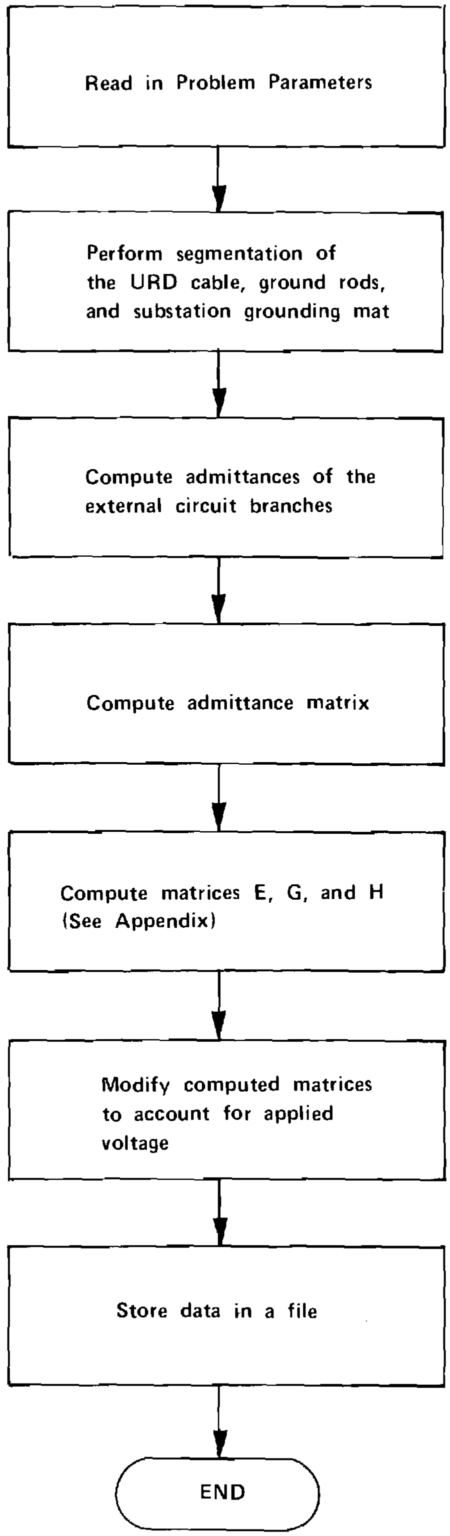


FIGURE 3.2 FLOW CHART OF SUBPROGRAM BCAB1

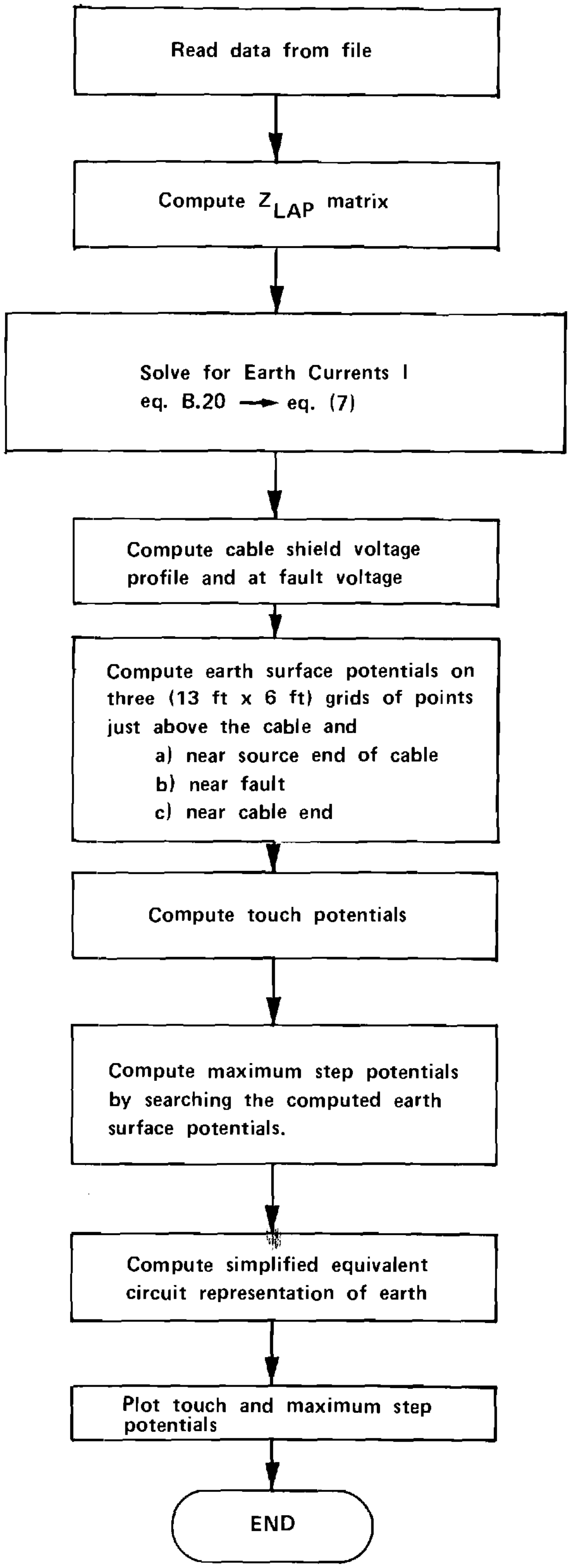


FIGURE 3.3 FLOW CHART OF SUBPROGRAM BCAB2

Appendix I.A

ELECTROMAGNETIC ANALYSIS

A method for the electromagnetic analysis of underground conductors in electrical contact with the earth is presented. The method combines integrals of Green's functions solutions to Laplace's Equation, superposition, and method of moments. The conductor is embedded in a two layer conducting medium located below a nonconducting medium. The depth of the boundary between the two conducting layers may be arbitrarily specified as well as the conductivities of the two layers.

The underground conductor is subdivided into a combination of N horizontal or vertical subsections. The subsections may be in either the upper or lower conducting regions. Each subsection is modeled as a cylindrical metallic conductor with an outer conducting jacket. The area, diameter, temperature and conductivity of the metallic conductor, and the thickness and conductivity of the jacket must be specified.

The conductor may be either a segment of an underground system or simply a single isolated length of conductor. In either case, electrical connection may be specified at the end or midpoint of any subsection. Conductor subsection lengths and burial depths must be specified. As the conductivities of both metallic conductor and the jacket are specified for each subsection of the conductor, many conductor configurations such as open sections, insulated jacket sections, sections without jackets, semiconducting jacketed sections may be modeled.

A.1 STATIC ANALYSIS OF 60 Hz PROBLEM

The wavelength for an electromagnetic field in a conducting region is given by

$$\lambda = \frac{2\pi}{\omega\sqrt{\mu\varepsilon}\,\{\frac{1}{2}\,[\sqrt{1 + (\frac{\sigma}{\omega\varepsilon})^2} + 1]\}^{\frac{1}{2}}} \tag{A-1}$$

The value of conductivity, σ, for soils commonly found in the continental United States ranges from 10^{-5} to 10^{-2} mhos/meter depending, primarily, on moisture content and soil type. The value of the permittivity, ε, for common soil types is not often reported; however, estimates obtained from the values of water, marble, mica, and wood yield a range of values of $2.0\,\varepsilon_o$ to $81.0\,\varepsilon_o$ where ε_o is the free space permittivity of value 8.854×10^{-12} F/m (Farads/meter). The value of the permeability, μ, for non-ferromagnetic soils is the same as the permeability of free space, namely 1.257×10^{-6} H/m (Henries/meter). At 60 Hz, the angular frequency, ω, is given by

$$\omega = 2\pi f = 377 \quad . \tag{A-2}$$

Using the extreme values for μ and ε given above yield the following extreme values of wavelength:

$$3.59 \text{ meters} \leq \lambda \leq 111.8 \text{ meters}$$

When the solution space of the field equations is much less than the propagation wavelength, no appreciable phase difference of the propagated wave exists between points in the space and propagation effects may therefore be ignored. Ignoring propagation effects converts the general electromagnetic analysis problem into an electromagnetic problem governed by Laplace's equation. The method of analysis presented below is an electromagnetostatic analysis and should not be applied to conducting regions where propagation effects are significant.

A.2 CURRENT CALCULATION FOR POINT SOURCE IN UPPER LAYER

The starting point for the development of this method is to solve for the voltage in three regions generated by a point of current I_p located in the middle medium. This solution is called the Green's Function for the problem. Figure A.1 shows the three regions, the point of current, and the reference coordinate system for this point problem. The cylindrical angle ϕ measured from the X axis in the x, y plane is not shown. The three regions are characterized by their conductivities and planar boundaries at Z=0 and Z=D. The solution to the problem is obtained from Laplace's Equation in cylindrical coordinates independent of the angle ϕ. The solution for the voltage is separable into functions Z(z) and R(r) as

$$V(r,z) = R(r)Z(z) \tag{A-3}$$

where V is the voltage at the cylindrical coordinates r and z and R and Z are functions to be determined. Laplace's Equation for this case reduces to

$$\nabla^2 V(r,z) = \frac{r}{R(r)} \frac{\partial}{\partial r} \left(r \frac{\partial R(r)}{\partial r}\right) + \frac{r^2}{Z(z)} \frac{\partial^2 Z(z)}{\partial z^2} = 0. \tag{A-4}$$

The general solution to the equation is given as

$$V(r,z) = \frac{I_p}{4\pi\sigma} \int_0^\infty \theta(k) J_0(kr) e^{+kz} dk \tag{A-5}$$

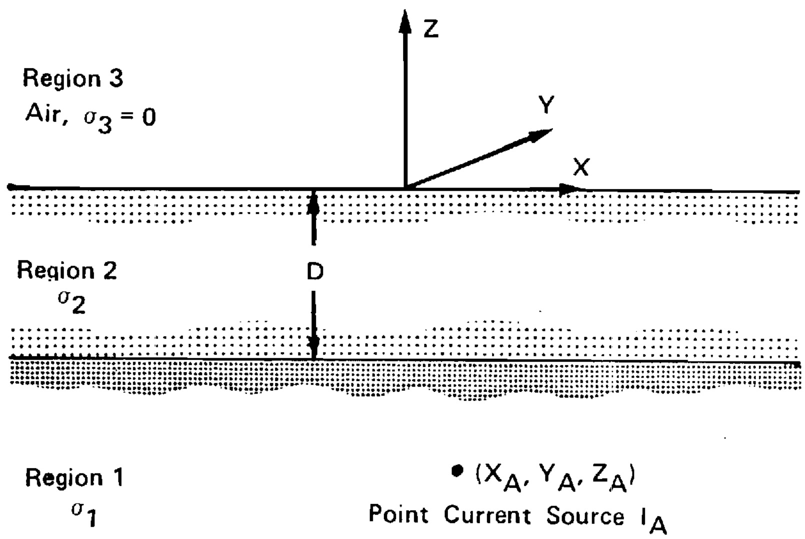


Figure A.1 Geometry of Earth Model

where $\theta(k)$ is an arbitrary function of k. The solution has two possible functional forms with respect to z and in general both forms must be employed.

The general solution for region 3 can now be written as follows:

$$V_3(r,z) = \frac{I_p}{4\pi\sigma_2} \int_0^{\infty} \Omega(k) J_0(kr) e^{-kz} dk, \quad z \geq 0 \tag{A-6}$$

where the +kz solution must have a zero coefficient, for $z \to +\infty$ the voltage must vanish. The conductivity σ_2 is used instead of σ_3 in the multiplier to keep the coefficients for all regions identical. The missing multiplying factor σ_2/σ_3, if needed, is absorbed in the unknown function $\Omega(k)$.

The general solution for region 2 is written as

$$V_2(r,z) = \frac{I_p}{4\pi\sigma_2} \left[\int_0^{\infty} J_0(kr) e^{-k|z-Z_1|} dk + \int_0^{\infty} \psi(k) J_0(kr) e^{-kz} dk + \int_0^{\infty} \theta(k) J_0(kr) e^{+kz} dk \right], \quad D \leq z \leq 0. \tag{A-7}$$

The solution for region 2 contains both the +kz and -kz general solutions. In addition, the first term of this solution is a forcing solution in the form of the known solution for a point current located at $z=Z_1$ of magnitude I_p in an infinite region of conductivity σ_2. The unknown functions $\psi(k)$ and $\theta(k)$ must then compensate for the forcing function.

The general solution for region 1 is written as

$$V_1(r,z) = \frac{I_p}{4\pi\sigma_2} \int_0^{\infty} \phi(k) J_0(kr) e^{+kz} dk, \quad z \leq D. \tag{A-8}$$

In this solution, the multiplying function for the -kz solution was set to zero in order that the voltage for $z \to -\infty$ would be zero.

The above set of three equations possesses four unknown functions $\Omega(k)$, $\psi(k)$, $\theta(k)$ and $\phi(k)$ which must be determined to solve for the voltages in the three regions. Four equations can be generated by applying boundary conditions to the solutions at the two boundaries z=0 and z=D. At each planar boundary the voltage on each side of the boundary must be continuous at the boundary (i.e.)

$$V_3(r,0) = V_2(r,0) \tag{A-9}$$

and

$$V_2(r,D) = V_1(r,D) \tag{A-10}$$

At each boundary, the current normal to the boundary must be continuous as it crosses the boundary (i.e.)

$$\sigma_3 \frac{\partial V_3(r,0)}{\partial z} = \sigma_2 \frac{\partial V_2(r,0)}{\partial z} \tag{A-11}$$

and

$$\sigma_2 \frac{\partial V_2(r,D)}{\partial z} = \sigma_1 \frac{\partial V_1(r,D)}{\partial z} \tag{A-12}$$

The solution to the four unknown functions as determined from the four boundary conditions is aided by the fact that for equality of integral equations of this type, the integrands must be equal. Since differentiation is not performed with respect to r in any of the four equations, all terms have the common factor $J_0(kr)$ which may be divided out of each side of the equations. Boundary condition Equations (A-9) and (A-10) result in the following algebraic equations:

$$\Omega(k) = e^{+kz_1} + \psi(k) + \theta(k) \tag{A-13}$$

$$\phi(k)e^{+kD} = e^{k(D-Z_1)} + \psi(k)e^{-kD} + \theta(k)e^{+kD} \tag{A-14}$$

Likewise, boundary condition Equations (A-10) and (A-11) result in the following algebraic equations

$$-\sigma_3\Omega(k) = -\sigma_2 e^{kZ_1} - \sigma_2\psi(k) + \sigma_2\theta(k) \tag{A-15}$$

$$\sigma_1\phi(k)e^{+kD} = \sigma_2 e^{k(D-Z_1)} - \sigma_2\psi(k)e^{-kD} + \sigma_2\theta(k)e^{+kD} \tag{A-16}$$

The solution of the four equations for the four unknown functions is straightforward but tedious. The results are given as

$$\Omega(k) = \frac{2\sigma_2 e^{kZ_1}}{\sigma_3+\sigma_2}\left[\frac{1-K_{12}e^{+2K(D-Z_1)}}{1-K_{12}K_{32}e^{+2kD}}\right] \tag{A-17}$$

$$\theta(k) = -K_{32}e^{kZ_1}\left[\frac{1-K_{12}e^{+2k(D-Z_1)}}{1-K_{12}K_{32}e^{+2kD}}\right] \tag{A-18}$$

$$\psi(k) = K_{12}e^{kZ_1}\left[\frac{K_{32}e^{+2kD}-e^{+2k(D-Z_1)}}{1-K_{12}K_{32}e^{+2kD}}\right] \tag{A-19}$$

$$\theta(k) = \frac{-2\sigma_2 e^{kZ_1}}{\sigma_1+\sigma_2}\left[\frac{K_{32}-e^{-2kZ_1}}{1-K_{12}K_{32}e^{+2kD}}\right] \tag{A-20}$$

where

$$K_{12} \triangleq \frac{\sigma_1-\sigma_2}{\sigma_1+\sigma_2}\ , \tag{A-21}$$

and

$$K_{32} \triangleq \frac{\sigma_3-\sigma_2}{\sigma_3+\sigma_2}. \tag{A-22}$$

Substitution of these functions into the voltage Equations (A-6), (A-7) and (A-8) yields integrals of the following form:

$$M = \int_0^\infty \frac{e^{-2kd}}{[1-K_{12}K_{32}e^{+2kD}]} J_0(kr)e^{\pm kz}dk \tag{A-23}$$

where d takes on the positive values $-Z_1$, $-D$, or $-(D+Z_1)$. The quantity

may be recognized as the sum of a power series of the form

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + x^4 + x^5 + \ldots \tag{A-24}$$

where $|x| < 1$.

It can be seen from the definition of K_{12} and K_{32} that each has a magnitude of one or less and since both $-D$ and k are positive, the magnitude of e^{+2kD} is always less than one except when k=0. The k=0 point is integrable in this form and therefore does not present a problem.

Expanding the denominator of the integrand of integral M in its power series representation, yields integrals of the following form

$$M_N = (K_{12}K_{32})^N \int_0^\infty J_0(kr)e^{\pm k(Z\mp 2d\pm 2ND)}dk \tag{A-25}$$

where N is any non-negative integer and d is as defined previously. Integrals of this form have the following value

$$M_N = \frac{(K_{12}K_{32})^N}{[r^2 + (z\mp 2d\pm 2ND)^2]^{\frac{1}{2}}} \tag{A-26}$$

Applying the above procedure of substituting the solution for the four unknown functions into the three voltage equations, and by expanding the denominators of each integral in a power series and integrating term by term, yields the following infinite series for the voltages in the three regions:

$$V_3(r,z) = \frac{I_p}{2\pi(\sigma_3+\sigma_2)}\left[\sum_{i=0}^{\infty}\frac{(K_{12}K_{32})^i}{[r^2 + (z-Z_1-2iD)^2]^{\frac{1}{2}}} - K_{12}\sum_{i=0}^{\infty}\frac{(K_{12}K_{32})^i}{[r^2 + (z+Z_1-2(i+1)D^2]^{\frac{1}{2}}}\right] \quad \text{for } z \geq 0 \tag{A-27}$$

$$\begin{aligned} V_2(r,z) = \frac{I_p}{4\pi\sigma_2}&\left[\frac{1}{[r^2 + (z-Z_1)^2]^{\frac{1}{2}}} - K_{12}\sum_{i=0}^{\infty}\frac{(K_{12}K_{32})^i}{[r^2 + (z+Z_1-2(i+1)D)^2]^{\frac{1}{2}}}\right. \\ &\left. + \sum_{i=1}^{\infty}\frac{(K_{12}K_{32})^i}{[r^2 + (z-Z_1-2iD)^2]^{\frac{1}{2}}}\right] - K_{32}\sum_{i=0}^{\infty}\frac{(K_{12}K_{32})^i}{[r^2 + (z-Z_1+2iD)^2]^{\frac{1}{2}}} \\ &+ \sum_{i=1}^{\infty}\frac{(K_{12}K_{32})^i}{[r^2 + (z-Z_1+2iD)^2]^{\frac{1}{2}}} \qquad \text{for } D \leq z \leq 0 \end{aligned} \tag{A-28}$$

and

$$V_1(r,z) = \frac{I_p}{2\pi(\sigma_1+\sigma_2)}\left[\sum_{i=0}^{\infty} \frac{(K_{12}K_{32})^i}{[r^2 + (z-Z_1+2iD)^2]^{\frac{1}{2}}}\right.$$

$$\left. - K_{32} \sum_{i=0}^{\infty} \frac{(K_{12}K_{32})^i}{[r^2 + (z+Z_1+2iD)^2]^{\frac{1}{2}}}\right] \qquad \text{for } z \le D \tag{A-29}$$

The above three equations are called the Green's function solution for the voltage in each medium due to a point of current in the medium 2.

A.3 CURRENT CALCULATION FOR POINT SOURCE IN LOWER LAYER

The Green's Function for the point current located in the lower layer is developed with the same procedure give above for the point current located in the upper layer. Results of the procedure are summarized below. The general solution for region 3 is written

$$V_3(r,z) = \frac{I_p}{4\pi\sigma_1} \int_0^{\infty} \Omega(k) J_0(kr) e^{-kz} dk, \quad z \ge 0 \tag{A-30}$$

The general solution for region 2 is written

$$V_2(r,z) = \frac{I_p}{4\pi\sigma_1}\left[\int_0^{\infty} \psi(k) J_0(kr) e^{-kz} dk + \int_0^{\infty} \theta(k) J_0(kr) e^{+kz} dz\right],$$

$$D \le z \le 0 \tag{A-31}$$

The general solution for region 1 which contains the point current I_p at (r-0, z=0) is written

$$V_1(r,z) = \frac{I_p}{4\pi\sigma_1}\left[\int_0^{\infty} J_0(kr) e^{-k|z-Z_1|} dk + \int_0^{\infty} \phi(k) J_0(kr) e^{kz} dz\right],$$

$$z \le D \tag{A-32}$$

The four boundary equations needed to solve for the four unknown functions $\Omega(k)$, $\psi(k)$, $\theta(k)$, and $\phi(k)$ are:

$$\Omega(k) = \psi(k) + \theta(k) \tag{A-33}$$

$$-\sigma_3\Omega(k) = -\sigma_2\psi(k) + \sigma_2\theta(k) \tag{A-34}$$

$$\psi(k)e^{-kD} + \theta(k)e^{kD} = e^{-k(D-Z_1)} + \phi(k)e^{kD} \tag{A-35}$$

$$-\sigma_2\psi(k)e^{-kD} + \sigma_2\theta(k)e^{kD} = -\sigma_1 e^{-k(D-Z_1)} + \sigma_1\phi(k)e^{kD} \tag{A-36}$$

Simultaneous solution of the four boundary equations yields

$$\Omega(k) = \frac{2\sigma_1}{(\sigma_1+\sigma_2)} \cdot \frac{2\sigma_2}{(\sigma_3+\sigma_2)} \left[\frac{e^{kZ_1}}{1-K_{12}K_{32}e^{2kD}}\right] \tag{A-37}$$

$$\psi(k) = \frac{2\sigma_1}{(\sigma_1+\sigma_2)} \left[\frac{e^{kZ_1}}{1-K_{12}K_{32}e^{2kD}}\right] \tag{A-38}$$

$$\theta(k) = -K_{32}\frac{2\sigma_1}{(\sigma_1+\sigma_2)} \left[\frac{e^{kZ_1}}{1-K_{12}K_{32}e^{2kD}}\right] \tag{A-39}$$

and

$$\phi(k) = \left[\frac{e^{kZ_1}(K_{12}e^{-2kD}-K_{32})}{1-K_{12}K_{32}e^{2kD}}\right] \tag{A-40}$$

where, as before,

$$K_{12} = \frac{\sigma_1-\sigma_2}{\sigma_1+\sigma_2} \tag{A-41}$$

$$K_{32} = \frac{\sigma_3-\sigma_2}{\sigma_3+\sigma_2} \tag{A-42}$$

The resulting voltages due to the point current in the lower layer are

$$V_3(r,z) = \frac{I_p\sigma_2}{\pi(\sigma_1+\sigma_2)(\sigma_3+\sigma_2)} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \frac{1}{(r^2 + (z-Z_1-2iD)^2)^{\frac{1}{2}}},$$

$$z \geq 0 \tag{A-43}$$

$$V_2(r,z) = \frac{I_p}{2\pi(\sigma_1+\sigma_2)} \left[\sum_{i=0}^{\infty} (K_{12}K_{32})^i \frac{1}{(r^2 + (z-Z_1-2iD)^2)^{\frac{1}{2}}}\right.$$

$$- K_{32} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \frac{1}{(r^2 + (z+Z_1+2iD)^2)^{\frac{1}{2}}}\Bigg] \quad \text{for } D \leq z \leq 0 \tag{A-44}$$

and

$$V_1(r,z) = \frac{I_p}{4\pi\sigma_1}\Bigg[\frac{1}{(r^2 + (z-Z_1)^2)^{\frac{1}{2}}} + K_{12} \sum_{i=0}^{\infty} (K_{12}K_{32})^i$$

$$\cdot \frac{1}{(r^2 + (z+Z_1+2(i-1)D)^2)^{\frac{1}{2}}} - K_{32} \sum_{i=0}^{\infty} (K_{12}K_{32})^i$$

$$\cdot \frac{1}{(r^2 + (z+Z_1+2iD)^2)^{\frac{1}{2}}}\Bigg], \quad z \leq D \tag{A-45}$$

The above three equations are called the Green's Function solution for the voltage in each medium due to a point of current in medium 1. These three equations, together with the three Green's Functions for the voltages due to a point of current in medium 2, will be integrated to find the voltages due to lines of horizontal and vertical currents in the following sections.

A.4 VOLTAGE PRODUCED BY HORIZONTAL LINES OF CURRENT

In this section the Green's Function solutions (point source solutions) are used in the determination of the voltages produced in the three regions due to a horizontal line of current located in the upper layer or the lower layer. This problem is solved by using the rectangular components of the cylindrical system shown in Figure A.1.

First, the superposition theorem is employed to find the voltage in the three regions as a summation of the voltages due to a distribution of point currents which are located on a horizontal line in the upper layer. The line is assumed to be parallel to the x axis with a length $2L_1$ with the center located at the rectangular coordinates (X_1, Y_1 and Z_1). Let the total current, I, be uniformly distributed along the length of the line, resulting in a current density of

$$\rho = \frac{I}{2L_1} \text{ (amps/meter)} \tag{A-46}$$

Now, let the line be segmented into infinitesimal segments of length dx_s. The current associated with each segment is $\rho dx_s = (I/2L_1)dx_s$. Then the contribution to the voltage at a point in (x,y,z) in any of the regions due to the segment with x-coordinate x_s can be obtained by the use of Equation (A-27), (A-28), or (A-29) with I_p replaced by $(I/2L_1)dx_s$, and r replaced with $\sqrt{(x-X_1)^2 + (y-Y_1)^2}$. The incremental voltage contributions can then be integrated to yield the total voltage due to the line current. For example, if we let $VX_{32}(x,y,z)$ be the voltage at a point (x,y,z) in region 3 due to a line of current in region 2, we have

$$VX_{32}(x,y,z) = \int_{X_1-L_1}^{X_1+L_1} \frac{I}{2L_1 2\pi(\sigma_3+\sigma_2)} \left[\sum_{i=0}^{\infty} \frac{(K_{12}K_{32})^i}{\sqrt{(x-x_s)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}} - K_{12} \sum_{i=0}^{\infty} \frac{(K_{12}K_{32})^i}{\sqrt{(x-x_s)^2+(y-Y_1)^2+(z-Z_1-2(i+1)D)^2}} \right] dx_s. \qquad \text{(A-47)}$$

Similar expressions are obtained for $VX_{22}(x,y,z)$ and $VX_{12}(x,y,z)$. Thus, each voltage expression is an infinite series of terms of the form

$$P = K \int_{X_1-L_1}^{X_1+L_1} \frac{\frac{I}{2L_1}\, dx_s}{\sqrt{(x-x_s)^2+(y-Y_1)^2+(z-Z_1 \pm 2E)^2}} \qquad \text{(A-48)}$$

where K and E are constant for each integration. The evaluation of this integral is straightforward for all points (x,y,z) not colinear with the line current. For points colinear with the line current but not on the line current, the denominator reduces to $x-x_s$ when the constant E is zero. The evaluation of this integral for points on the line current will be presented later. In all cases, except for points on the line current, the evaluation of this integral is determined as

$$P = K \frac{I}{2L_1} [F(x-X_1, y-Y_1, z-Z_1, L_,)] \qquad \text{(A-49)}$$

where

$$F(t,u,v,L) \triangleq \ln \left[\frac{\sqrt{(t+L)^2+u^2+v^2} + t + L}{\sqrt{(t-L)^2+u^2+v^2} + t - L} \right] \qquad \text{(A-50)}$$

The voltage at point (x,y,z) due to the line current then becomes

$$VX_{32}(x,y,z) = \frac{I}{4\pi L_1(\sigma_3+\sigma_2)}\left[\sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z-Z_1, L_1)\right.$$

$$\left. - K_{12} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z+Z_1-2(i+1)D, L_1)\right],$$

$$\text{for } z \geq 0 \qquad \text{(A-51a)}$$

and

$$VX_{22}(x,y,z) = \frac{I}{8\pi L_1\sigma_2}\left[F(x-X_1, y-Y_1, z-Z_1, L_1)\right.$$

$$- K_{12} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-v_1, z+Z_1-2(i+1)D, L_1)$$

$$+ \sum_{i=1}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z-Z_1+2iD, L_1)$$

$$- K_{32} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z+Z_1+2iD, L_1)$$

$$\left. + \sum_{i=1}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z-Z_1-2iD, L_1)\right]$$

for $D \leq z \leq 0$ and (x,y,z) not colinear with line current. (A-51b)

and

$$VX_{12}(x,y,z) = \frac{I}{4\pi L_1(\sigma_1+\sigma_2)}\left[\sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z-Z_1+2iD, L_1)\right.$$

$$\left. - K_{32} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z+Z_1+2iD, L_1)\right]$$

$$\text{for } z \leq D \qquad \text{(A-51-c)}$$

A similar integration leads to the following results for horizontal line current sources of length $2L_1$ and diameter 2a with center at (X_1,Y_1,Z_1) located in region 1 such that $Z_1 < D-a$

$$VX_{31}(x,y,z) = \frac{I\sigma_2}{2\pi L_1(\sigma_1+\sigma_2)(\sigma_3+\sigma_2)} \sum_{i=0}^{\infty} (K_{12}K_{32})^i$$

$$\cdot\ F(x-X_1, y-Y_1, z-Z_1-2iD, L_1) \quad \text{for } z \geq 0 \qquad \text{(A-51d)}$$

$$VX_{21}(x,y,z) = \frac{I}{4\pi L_1(\sigma_1+\sigma_2)} \left[\sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z-Z_1-2iD, L_1) \right.$$

$$\left. - K_{32} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z+Z_1+2iD, L_1) \right]$$

$$\text{for } D \leq z \leq 0 \qquad \text{(A-51e)}$$

$$VX_{11}(x,y,z) = \frac{I}{8\pi L_1\sigma_1} \left[F(x-X_1, y-Y_1, z-Z_1, L_1) \right.$$

$$+ K_{12} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z+Z_1+2(i+1)D, L_1)$$

$$\left. - K_{32} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, F(x-X_1, y-Y_1, z+Z_1+2iD, L_1) \right]$$

for $z \leq D$ and (x,y,z) not on line current (A-51f)

Voltage equations with form similar to these six equations will frequently appear in this paper, so it is convenient to define the following functions to simplify the expression of these equations.

Let:

$$S_{32}\{G(x,y,z)\} \triangleq \frac{I}{4\pi L_1(\sigma_3+\sigma_2)} \left[\sum_{i=0}^{\infty} (K_{12}K_{32})^i \, G(x-X_1, y-Y_1, z-Z_1) \right.$$

$$\left. - K_{12} \sum_{i=0}^{\infty} (K_{12}K_{32})^i \, G(x-X_1, y-Y_1, z-Z_1-2iD-2D) \right] \qquad \text{(A-52a)}$$

$$S_{22}\{G(x,y,z)\} \triangleq \frac{I}{8\pi L_1\sigma_2}\Bigg[G(x-X_1,y-Y_1,z-Z_1)$$

$$- K_{12}\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z+Z_1-2iD-2D)$$

$$+ \sum_{i=1}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z-Z_1+2iD)$$

$$- K_{32}\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z+Z_1+2iD)$$

$$+ \sum_{i=1}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z-Z_1-2iD)\Bigg] \qquad \text{(A-52b)}$$

$$S_{12}\{G(x,y,z)\} = \frac{I}{4\pi L_1(\sigma_1+\sigma_2)}\Bigg[\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z-Z_1+2iD)$$

$$- K_{32}\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z+Z_1+2iD)\Bigg] \qquad \text{(A-52c)}$$

$$S_{31}\{G(x,y,z)\} = \frac{I}{2\pi L_1(\sigma_1+\sigma_2)}\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z-Z_1-2iD) \qquad \text{(A-52d)}$$

$$S_{21}\{G(x,y,z)\} = \frac{I}{4\pi L_1(\sigma_1+\sigma_2)}\Bigg[\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z-Z_1-2iD)$$

$$- K_{32}\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z+Z_1+2iD)\Bigg] \qquad \text{(A-52e)}$$

$$S_{11}\{G(x,y,z)\} = \frac{I}{8\pi L_1\sigma_1}\Bigg[G(x-X_1,y-Y_1,z-Z_1)$$

$$+ K_{12}\sum_{i=0}^{\infty}(K_{12}K_{32})^i\, G(x-X_1,y-Y_1,z+Z_1+2iD-2D)$$

$$- K_{32} \sum_{i=0}^{\infty} (K_{12}K_{32})^{i}\, G(x-X_1, y-Y_1, z+Z_1+2iD)\Bigg] \qquad \text{(A-52f)}$$

Let these functions have a special property such that when G(x,y,z) on the left hand side becomes G(x,y,z). The domain elements of the G's on the right hand side would also change, e.g.

$$S_{31}\{G(z,y,x)\} = \frac{I}{4\pi L_1(\sigma_1+\sigma_2)} \sum_{i=0}^{\infty} (K_{12}K_{32})^{i}\, G(z-Z_1-2iD, y-Y_1, x-X_1)$$

and

$$S_{32}\{G(y,z,x)\} = \frac{I}{4\pi L_1(\sigma_3+\sigma_2)} \Bigg[\sum_{i=0}^{\infty} (K_{12}K_{32})^{i}\, G(y-Y_1, z-Z_1, x-X_1)$$

$$-K_{12} \sum_{i=0}^{\infty} (K_{12}K_{32})^{i}\, G(y-Y_1, z-Z_1-2iD-2D, x-X_1)\Bigg]$$

A.5 VOLTAGE PRODUCED BY VERTICAL LINES OF CURRENT

In this section the Green's Function solutions are used in the determination of the voltages produced in the three regions due to a vertical line of current located in either the upper layer or lower layer.

The derivation proceeds in the same sequence used in the derivation of the voltage due to horizontal lines of current presented above. The current density is assumed to be uniformly distributed over the vertical line of length 2L. The Green's Functions for a point current located in the upper layer are then integrated along the vertical z dimension of the line of current term by term. The following integral is representative of such terms:

$$P = K \int_{Z_1-L_1}^{Z_1+L_1} \frac{\frac{I}{2L_1}\, dz_s}{\sqrt{(x-X_1)^2+(y-Y_1)^2+(z-z_s\pm 2E)^2}} \qquad \text{(A-53)}$$

where K and E are constant for each integration. The evaluation of the integral is straightforward for all points (x,y,z) not on line current.

For point (x,y,z) not on the line, the integral may be evaluated as follows:

$$P = K\,\frac{I}{2L_1}[F(z-Z_1-2iD, y-Y_1, x-X_1, L_1)] \tag{A-54}$$

Let $G(t,u,v) = F(t,u,v,L_1)$.

Then voltages due to the vertical current located in region 2 for any point (x,y,z) not on the line current are:

$$VZ_{32}(x,y,z) = S_{32}\;G(x,y,z) \qquad z \geq 0 \tag{A-55a}$$

$$VZ_{22}(x,y,z) = S_{22}\;G(x,y,z) \qquad 0 \geq z \geq D \tag{A-55b}$$

$$VZ_{12}(x,y,z) = S_{12}\;G(x,y,z) \qquad z \leq D \tag{A-55c}$$

The equations for the voltage produced by a vertical line of current of length $2L_1$ and diameter 2a with center at (X_1,Y_1,Z_1) located in region 1 are developed in a similar fashion. The results are:

$$VZ_{31}(x,y,z) = S_{31}\;G(z,x,y) \qquad z \geq 0 \tag{A-55d}$$

$$VZ_{21}(x,y,z) = S_{21}\;G(z,x,y) \qquad 0 \geq z \geq D \tag{A-55e}$$

$$VZ_{11}(x,y,z) = S_{11}\;G(z,x,y) \qquad z \leq D \tag{A-55f}$$

It can be shown that the voltage produced by a line current becomes the same as the voltage produced by a cylindrical tube of current of radius a for points beyond several diameters from the tube. The primary effect of the tube diameter is on the self resistance of the conductor, covered subsequently.

A.6 POTENTIAL OF CONDUCTING SEGMENTS

The equations given above are not directly applicable to the computation of potential on a second line conductor. That is, if a second (perfect) conductor were located in region 1 centered at coordinates (x,y,z) Equation (A-51f) would indicate that the potential on the equation resulting from the source conductor would vary along the length of the second conductor. On the other hand, since the conductor is lossless, the potential is constrained to be uniform. Following the work of Tagg and Sunde, in order to satisfy this constraint, the assumption is made that the voltage of the perfect conductor is the average of the potentials calculated along the line of the conductor. This can be accomplished by integrating the voltage along the line of the second conductor and dividing by the conductor length.

The averaging of the voltage along the conductor results in 36 different voltage equations due to the fact that the source conductor may be x-directed, y-directed or z-directed and may be in region 1 or 2. Likewise, the second conductor can also have different orientation and location. These 36 equations can be written in terms of two basic functions as will be shown in the next 2 sections.

A.7 PARALLEL CONFIGURATION

Let the second conductor have length of 2L, be located in region 2 with center (x,y,z) and the source conductor have length of $2L_1$ with center (X_1,Y_1,Z_1). The average potential terms from Equations (A-49) and (A-50) have the following form:

$$VX = \frac{K}{2L} \int_{x-L_1}^{x+L_1} \ln \frac{\sqrt{(x_p-X_1+L)^2+(y-Y_1)^2+(z-Z_1+E)^2}+x_p-X_1+L}{\sqrt{(x_p-X_1-L)^2+(y-Y_1)^2+(z-Z_1+E)^2}+x_p-X_1-L}\, dx_p \qquad \text{(A-56)}$$

where both conductors are assumed to be oriented in the x-direction.

This integration of each of the voltage equations yields the following equations:

$$VX_{32}(x,y,z) = \frac{I}{8\pi LL_1(\sigma_3+\sigma_2)} \left[\sum_{i=0}^{\infty} (K_{12}K_{32})^i \; H'(x-X_1, y-Y_1, z-Z_1, L, L_1) \right.$$
$$\left. - K_{12} \sum_{i=0}^{\infty} (K_{12}K_{32})^i H'(x-X_1, y-Y_1, z+Z_1-2iD-2D, L, L_1) \right]$$
$$\text{for } z \geq 0 \qquad \text{(A-57)}$$

where

$$H'(t,u,v,L,L_1) \triangleq \int_{t-L}^{t+L} F(t_p,u,v,L_1)\,dt_p$$

$$= \int_{t-L_1}^{t+L_1} \ln \frac{\sqrt{(t_p+L_1)^2+u^2+v^2}+t_p-L_1}{\sqrt{(t_p-L_1)^2+u^2+v^2}+t_p-L_1}\, dt_p \qquad \text{(A-58)}$$

since

$$\int \ell n(x + \sqrt{x^2+a^2})dx = x \ \ell n(x + \sqrt{x^2+a^2}) - \sqrt{x^2+a^2}$$

$H'(t,u,v,L,L_1)$ may be written as

$$\begin{aligned} H'(t,u,v,L,L_1) \triangleq &+ \sqrt{(t-L+L_1)^2+u^2+v^2} - (t-L+L_1)\ell n(t-L+L_1 + \sqrt{(t-L+L_1)^2+u^2+v^2}) \\ &- \sqrt{(t+L+L_1)^2+u^2+v^2} + (t+L+L_1)\ell n(t+L+L_1 + \sqrt{(t+L+L_1)^2+u^2+v^2}) \\ &- \sqrt{(t-L-L_1)^2+u^2+v^2} + (t-L-L_1)\ell n(t-L-L_1 + \sqrt{(t-L-L_1)^2+u^2+v^2}) \\ &+ \sqrt{(t+L-L_1)^2+u^2+v^2} - (t+L-L_1)\ell n(t+L-L_1 + \sqrt{(t+L-L_1)^2+u^2+v^2}) \end{aligned} \quad (A-59)$$

Again we abbreviate the notation as:

$$H(t,u,v) \triangleq \frac{1}{2L} H'(t,u,v,L,L_1)$$

and write the votlage equation in terms of Equation (A-52) then the voltage equations become:

$$VX_{32}(x,y,z) = S_{32}\ H(x,y,z) \qquad z \geq 0 \qquad (A-60a)$$

$$VX_{22}(x,y,z) = S_{22}\ H(x,y,z) \qquad 0 \geq z \geq D \qquad (A-60b)$$

$$VX_{12}(x,y,z) = S_{12}\ H(x,y,z) \qquad z \leq D \qquad (A-60c)$$

The equation of the voltage due to a source line current of $2L_1$ length center at (x_1,Y_1,Z_1) located in region 1 are:

$$VX_{31} = S_{31}\ H(x,y,z) \qquad z \geq 0 \qquad (A-60d)$$

$$VX_{21} = S_{21}\ H(x,y,z) \qquad 0 \geq z \geq D \qquad (A-60e)$$

$$VX_{11} = S_{11}\ H(x,y,z) \qquad z \leq D \qquad (A-60f)$$

For both conductors y-directed, the six voltage equations are:

For source at region 2

$$VY_{32} = S_{32}\ H(y,x,z) \qquad z \geq 0 \qquad (A-61a)$$

$$VY_{22} = S_{22}\ H(y,x,z) \qquad 0 \geq z \geq D \qquad \text{(A-61b)}$$

$$VY_{12} = S_{12}\ H(y,x,z) \qquad z \leq D \qquad \text{(A-61c)}$$

For source at region 1

$$VY_{31} = S_{31}\ H(y,x,z) \qquad z \geq 0 \qquad \text{(A-61d)}$$

$$VY_{21} = S_{21}\ H(y,x,z) \qquad 0 \geq z \geq D \qquad \text{(A-61e)}$$

$$VY_{11} = S_{11}\ H(y,x,z) \qquad z \leq D \qquad \text{(A-61f)}$$

For both conductor z-directed we can integrate equation similar to the x-directed case and obtain the following equations:

For source at region 2

$$VZ_{32} = S_{32}\ H(z,y,x) \qquad z \geq 0 \qquad \text{(A-62a)}$$

$$VZ_{22} = S_{22}\ H(z,y,x) \qquad 0 \geq z \geq D \qquad \text{(A-62b)}$$

$$VZ_{12} = S_{12}\ H(z,y,x) \qquad z \leq D \qquad \text{(A-62c)}$$

For source at region 1

$$VZ_{31} = S_{31}\ H(z,y,x) \qquad z \geq 0 \qquad \text{(A-62d)}$$

$$VZ_{21} = S_{21}\ H(z,y,x) \qquad 0 \geq z \geq D \qquad \text{(A-62e)}$$

$$VZ_{11} = S_{11}\ H(z,y,x) \qquad z \leq D \qquad \text{(A-62f)}$$

A.8 PERPENDICULAR CONFIGURATION

When the two conductors are not parallel, the integration has a different form. For example, assume the first conductor has length of $2L_1$, is directed in x-direction and the second conductor is y-directed and has length of 2L. The average voltage equation terms then have the basic form

$$VXY = \frac{K}{2L_1} \int_{y-L}^{y+L} \ell n \frac{\sqrt{(x-X_1+L_1)^2+(y_p-Y_1)^2+(z-Z_1+E)^2}+x-X_1+L_1}{\sqrt{(x-X_1-L_1)^2+(y_p-Y_1)^2+(z-Z_1+E)^2}+x-X_1+L_1}\, dy_p$$

$$= \frac{K}{2L_1} N'(x-X_1, y-Y_1, z-Z_1, L_1) \tag{A-63}$$

where

$$N'(t,u,v,L,L_1) \triangleq \int_{u-L}^{u+L} F(t,u_p,v,L,L_1)\, du_p$$

$$= \int_{u-L}^{u+L} \ln\left[\frac{\sqrt{(t+L_1)^2+u_p^2+v^2}+t+L_1}{\sqrt{(t-L_1)^2+u_p^2+v^2}+t-L_1}\right] du_p \tag{A-64}$$

Since

$$\int \ln(A + \sqrt{r^2+B^2})dr = -r + A \ln(2r + 2\sqrt{r^2+B^2})$$

$$+ \sqrt{B^2-A^2} \sin^{-1}\left(\frac{-A\sqrt{r^2+B^2}-B}{B\sqrt{r^2+B^2}+A} + r \ln(A + \sqrt{r^2+B^2})\right)$$

then

$$N'(t,u,v,L,L_1) = + (u+L) \ln\left[\frac{(t+L_1) + \sqrt{(t+L_1)^2+(u+L)^2+v^2}}{(t-L_1) + \sqrt{(t-L_1)^2+(u+L)^2+v^2}}\right]$$

$$+ (t+L_1) \ln\left[\frac{(u+L) + \sqrt{(t+L_1)^2+(u+L)^2+v^2}}{(u-L) + \sqrt{(t+L_1)^2+(u-L)^2+v^2}}\right]$$

$$+ (u-L) \ln\left[\frac{(t-L_1) + \sqrt{(t-L_1)^2+(u-L)^2+v^2}}{(t+L_1) + \sqrt{(t+L_1)^2+(u-L)^2+v^2}}\right]$$

$$+ (t-L_1) \ln\left[\frac{(u-L) + \sqrt{(t-L_1)^2+(u-L)^2+v^2}}{(u+L) + \sqrt{(t-L_1)^2+(u+L)^2+v^2}}\right]$$

$$+ |v|\left\{\sin^{-1} \frac{-(t+L_1)\sqrt{(t+L_1)^2+(u+L)^2+v^2}-(t+L_1)^2-v^2}{\sqrt{[(t+L_1)^2+v^2][(t+L_1)^2+(u+L)^2+v^2]}+(t+L_1)}\right.$$

$$- \sin^{-1} \frac{-(t-L_1)\sqrt{(t-L_1)^2+(u+L)^2+v^2}-(t-L_1)^2-v^2}{\sqrt{[(t-L_1)^2+v^2][(t-L_1)^2+(u+L)^2+v^2]}+(t+L_1)}$$

$$- \sin^{-1} \frac{-(t+L_1)\sqrt{(t+L_1)^2+(u-L)^2+v^2}-(t+L_1)^2-v^2}{\sqrt{[(t+L_1)^2+v^2][(t+L_1)^2+(u-L)^2+v^2]}+(t+L_1)}$$

$$\left. + \sin^{-1} \frac{-(t-L_1)\sqrt{(t-L_1)^2+(u-L)^2+v^2}-(t-L_1)^2-v^2}{\sqrt{[(t-L_1)^2+v^2][(t-L_1)^2+(u-L)^2+v^2]}+(t-L_1)} \right\} \qquad \text{(A-65)}$$

Again we abbreviate the notation as:

$$N(t,u,v) = \frac{1}{2L} N'(t,u,v,L,L_1) \quad .$$

Similar to the parallel configuration, we can express the average voltage equations for the perpendicular configurations in terms of the N function. For conductors having the same dimensions as before, these equations become:

For X-Y configuration, X-directed source conductor located in region 2

$$VXY_{32} = S_{32}\, N(x,y,z) \qquad z \geq 0 \qquad \text{(A-66a)}$$

$$VXY_{22} = S_{22}\, N(x,y,z) \qquad 0 \geq z \geq D \qquad \text{(A-66b)}$$

$$VXY_{12} = S_{12}\, N(x,y,z) \qquad D \leq z \qquad \text{(A-66c)}$$

For X-Y configuration, X-directed source conductor located in region 1

$$VXY_{31} = S_{31}\, N(x,y,z) \qquad z \geq 0 \qquad \text{(A-66d)}$$

$$VXY_{21} = S_{21}\, N(x,y,z) \qquad 0 \geq z \geq D \qquad \text{(A-66e)}$$

$$VXY_{11} = S_{11}\, N(x,y,z) \qquad D \leq z \qquad \text{(A-66f)}$$

For X-Y configuration, Y-directed source conductor located in region 2

$$VYX_{32} = S_{32}\, N(y,x,z) \qquad z \geq 0 \qquad \text{(A-67a)}$$

$$VYX_{22} = S_{22}\, N(y,x,z) \qquad 0 \geq z \geq D \qquad \text{(A-67b)}$$

$$VYX_{12} = S_{12}\, N(y,x,z) \qquad D \leq z \qquad \text{(A-67c)}$$

For Y-X configuration, Y-directed source conductor located in region 1

$$VYX_{31} = S_{31}\ N(y,x,z) \qquad z \geq 0 \qquad \text{(A-67d)}$$

$$VYX_{21} = S_{21}\ N(y,x,z) \qquad 0 \geq z \geq D \qquad \text{(A-67e)}$$

$$VYX_{11} = S_{11}\ N(y,x,z) \qquad D \leq z \qquad \text{(A-67f)}$$

For X-Z configuration, X-directed source conductor located in region 2

$$VXZ_{32} = S_{32}\ N(x,z,y) \qquad z \geq 0 \qquad \text{(A-68a)}$$

$$VXZ_{22} = S_{22}\ N(x,z,y) \qquad 0 \geq z \geq D \qquad \text{(A-68b)}$$

$$VXZ_{12}\ S_{12}\ N(x,z,y) \qquad D \leq z \qquad \text{(A-68c)}$$

For X-Z configuration, X-directed source conductor located in region 1

$$VXZ_{31} = S_{31}\ N(x,z,y) \qquad z \geq 0 \qquad \text{(A-68d)}$$

$$VXZ_{21} = S_{21}\ N(x,z,y) \qquad 0 \geq z \geq D \qquad \text{(A-68e)}$$

$$VXZ_{11} = S_{11}\ N(x,z,y) \qquad D \leq z \qquad \text{(A-68f)}$$

For Z-X configuration, Z-directed source conductor located in region 2

$$VZX_{32} = S_{32}\ N(x,z,y) \qquad z \geq 0 \qquad \text{(A-69a)}$$

$$VZX_{22} = S_{22}\ N(x,z,y) \qquad 0 \geq z \geq D \qquad \text{(A-69b)}$$

$$VZX_{12} = S_{12}\ N(x,z,y) \qquad D \leq z \qquad \text{(A-69c)}$$

For Z-X configuration, Z-directed source conductor located in region 1

$$VZX_{31} = S_{31}\ N(x,z,y) \qquad z \geq 0 \qquad \text{(A-69d)}$$

$$VZX_{21} = S_{21}\ N(x,z,y) \qquad 0 \geq z \geq D \qquad \text{(A-69e)}$$

$$VZX_{11} = S_{11}\ N(x,z,y) \qquad D \leq z \qquad \text{(A-69f)}$$

For Y-Z configuration, Y-directed source conductor located in region 2

$$VYZ_{32} = S_{32}\ N(y,z,x) \qquad z \geq 0 \qquad \text{(A-70a)}$$

$$VYZ_{22} = S_{22}\ N(y,z,x) \qquad 0 \geq z \geq D \qquad \text{(A-70b)}$$

$$VYZ_{12} = S_{12}\ N(y,z,x) \qquad D \leq z \qquad \text{(A-70c)}$$

For Y-Z configuration, Y-directed source conductor located in region 1

$$VYZ_{31} = S_{31}\ N(y,z,x) \qquad z \geq 0 \qquad \text{(A-70d)}$$

$$VYZ_{21} = S_{21}\ N(y,z,x) \qquad 0 \geq z \geq D \qquad \text{(A-70e)}$$

$$VYZ_{11} = S_{11}\ N(y,z,x) \qquad D \leq z \qquad \text{(A-70f)}$$

For Z-Y configuration, Z-directed source conductor located in region 2

$$VZY_{32} = S_{32}\ N(z,y,x) \qquad z \geq 0 \qquad \text{(A-71a)}$$

$$VZY_{22} = S_{22}\ N(z,y,x) \qquad 0 \geq z \geq D \qquad \text{(A-71b)}$$

$$VZY_{12} = S_{12}\ N(z,y,x) \qquad D \leq z \qquad \text{(A-71c)}$$

For Z-Y configuration, Z-directed source conductor located in region 1

$$VZY_{31} = S_{31}\ N(z,y,x) \qquad z \geq 0 \qquad \text{(A-71d)}$$

$$VZY_{21} = S_{21}\ N(z,y,x) \qquad 0 \geq z \geq D \qquad \text{(A-71e)}$$

$$VZY_{11} = S_{11}\ N(z,y,x) \qquad D \leq z \qquad \text{(A-71f)}$$

A.9 SELF POTENTIAL

The equations thus far devided are restricted, because the equations for the voltage at any point due to line current source are not valid when the point is on the line current. It will be necessary in what follows to be able to evaluate this voltage.

The case of an X-directed line current in region 2 is used as an example. Examination of the expressions for VX_{12}, VX_{22} and VX_{32} show that only the first term of $VX_{22}(x,y,z)$ becomes undefined for a point on the conductor (i.e. $y=Y_1$, $z=Z_1$, $X_1-L_1 \leq x \leq X_1+L_1$). Define this term to be $VX_{22}(x,y,z)$. It is noted that $VX_{22}(x,y,z)$ has physical significance. This term is recognized as the voltage at (x,y,z) which would have been produced had the problem been composed of an infinite medium of homogeneous conductivity σ_2 with a line of current of length 2L, directed parallel to the x axis and having a center at (X_1,Y_1,Z_1). The solution of this problem is now obtained with an alternate method and will be substituted for the undefined term in VX_{22} whenever the point voltage evaluation lies on the current line.

For the purposes of calculating the potentials on the line of current in an infinite medium, the line of current may be replaced with a tube of current of length 2L and diameter 2a. A total current I is leaving the surface of the tube and is uniformly distributed over the surface area of the tube with current density ρ given by

$$\rho = \frac{I}{(2\pi a)(2L_1)} = \frac{I}{4\pi a L_1}$$

The equation for the potential in an infinite medium of homogeneous conductivity σ_2 is given by the surface integral of the current distribution weighted by $1/4\pi r\sigma_2$, where r is the distance measured from each current element to the point of voltage evaluation. For a current tube parallel to the x-axis centered at (X_1,Y_1,Z_1) the voltage on the tube center line ($y=Y_1$, $z=Z_1$) is

$$VX'_{22}(x,Y_1,Z_1) = \frac{1}{4\pi\sigma_2}\int_0^{2\pi}\int_{X_1-L_1}^{X_1+L_1}\frac{\frac{I}{4\pi a L_1}}{\sqrt{(x-x_s)^2+a^2}}\,dx_s\,d\alpha \tag{A-72}$$

where α is defined in Figure A.2.

Evaluating the integral yields

$$VX'_{22}(x,Y_1,Z_1) = \frac{I}{8\pi\sigma_2 L}\,\ell n\left[\frac{\sqrt{(x-X_1+L)^2+a^2}+x-X_1+L}{\sqrt{(x-X_1-L)^2+a^2}+x-X_1-L}\right] \tag{A-73}$$

Thus, for cases in which the voltage of the line current must be evaluated on the line current, the first term of Equation (A-51b) is replaced with Equation (A-72).

Comparison of Equation (A-72) with the term of Equation (A-51b) shows that they are identical when a=0 and that the two results become asymptomatically equal as $|x-X_1|$ increases beyond L. As an example, let $|x-X_1|$ be greater than L_1 by 10 radii, 10a; the voltage derived for the tube of current becomes

$$VX'_{22}(10a+X_1+L,Y_1,Z_1) = \frac{I}{8\pi\sigma_2 L_1}\,\ell n\left[\frac{\sqrt{400a^2+a^2}+20a}{\sqrt{100a^2+a^2}+10a}\right]$$

$$= \frac{I}{8\pi\sigma_2 L_1}\,\ell n\left[\frac{\sqrt{401a^2}+20a}{\sqrt{101a^2}+10a}\right]$$

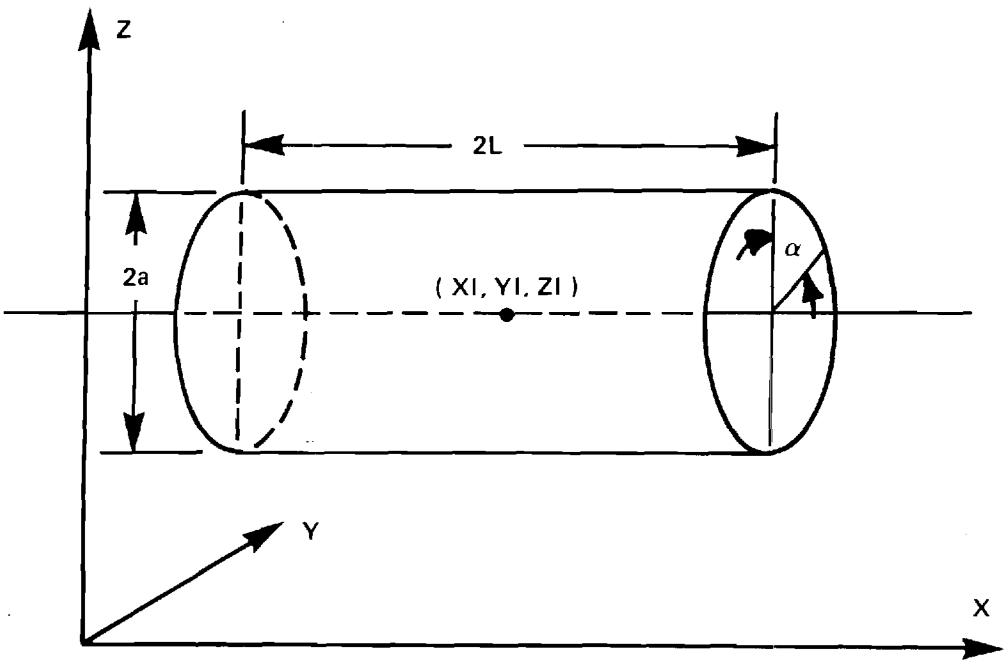


FIGURE A.2 GEOMETRY OF CURRENT TUBE

$$\frac{I}{8\pi\sigma_2 L_1} \ln \left[\frac{\sqrt{400a^2}+20a}{\sqrt{100a^2}+10a} \right] \tag{A-74}$$

The last expression is equal to the first term of Equation (A-51b) when evaluated on a line colinear with the line source.

The above analysis shows that the voltage equations for lines of currents are the same as the equations of tubes of currents with finite diameter as long as the evaluation of the voltages is performed <u>many diameters from the tube</u>.

The self voltage of a tube of current may be calculated as the average voltage along the axis of the tube, similar to the average voltage applied earlier.

For the case of a conductor located in region 2 and X-directed, the voltage has the form:

$$W = \int_{X-L}^{X+L} VX'_{22}(x_p, Y_1, Z_1)\, dx_p$$

$$= \int_{X-L}^{X+L} \ln \left[\frac{\sqrt{(x_p-X_1+L_1)^2+a^2}+(x_p-X_1+L_1)}{\sqrt{(x_p-X_1-L_1)^2+a^2}+(x_p-X_1-L_1)} \right] dx_p \tag{A-75}$$

Again since

$$\int \ln(x + \sqrt{x^2+A^2})\, dx = x \ln(x + \sqrt{x^2+A^2}) - \sqrt{x^2+A^2}$$

then

$$W = [(x_p-X_1+L_1) \ln(x_p-X_1+L_1 + \sqrt{(x_p-X_1+L_1)^2+a^2}) - \sqrt{(x_p-X_1+L_1)^2+a^2}$$

$$- (x_p-X_1-L_1) \ln(x_p-X_1-L_1 + \sqrt{(x_p-X_1-L_1)^2+a^2}) + \sqrt{(x_p-X_1-L_1)^2+a^2}] \Big|_{x-L}^{x+L}$$

$$= (x+L-X_1+L_1) \ln(x+L-X_1+L_1 + \sqrt{(x+L-X_1+L_1)^2+a^2})$$

$$- (x-L-X_1+L_1) \ln(x-L-X_1+L_1 + \sqrt{(x-L-X_1+L_1)^2+a^2})$$

$$- (x+L-X_1-L_1) \ln(x+L-X_1-L_1 + \sqrt{(x+L-X_1-L_1)^2+a^2})$$

$$+ (x-L-X_1-L_1)\ \ln(x-L-X_1-L_1 + \sqrt{(x-L-X_1-L_1)^2+a^2})$$

$$- \sqrt{(x+L-X_1+L_1)^2+a^2} + \sqrt{(x-L-X_1+L_1)^2+a^2} + \sqrt{(x+L-X_1-L_1)^2+a^2}$$

$$- \sqrt{(x-L-X_1-L_1)^2+a^2} \tag{A-76}$$

For $x=X_1$, $L=L_1$

$$W = 2L\left\{\ln\left[\frac{2L + \sqrt{4L^2+a^2}}{-2L + \sqrt{4L^2+a^2}}\right] - 2\sqrt{1 + \frac{a^2}{4L^2}} + 2\sqrt{\frac{a^2}{4L^2}}\right\} \tag{A-77}$$

This equation may be written using the previously defined H function as

$$W = H(0,z,0,L,L)$$

Therefore, to evaluate the average self potential for any tube of current of any orientation the voltage equation developed for two parallel conductors located in the same region are used and evaluated at

$$x-X_1 = 0, \quad y-Y_1 = a, \quad z-Z_1 = 0 \quad .$$

A.10 MUTUAL AND SELF RESISTANCE

The mutual and self resistance are derived in this section using the voltage Equations (A-60), (A-61), (A-62), (A-66), (A-67) and (A-68) developed before. All those equations have the general form of

$$V(x,y,z,X_1,Y_1,Z_1,I) = I\ F(x,y,z,X_1,Y_1,Z_1) \tag{A-78}$$

When the dimensions of the conductors are fixed, V becomes a function of location and current. Examination of all voltage equations thus far reveals that V is linearly dependent on the current I leaving the conductor. Mutual resistance between two conductors is defined as

$$RM(x,y,z,X_1,Y_1,Z_1) = \frac{V(x,y,z,X_1,Y_1,Z_1,I)}{I}$$

$$= F(x,y,z,X_1,Y_1,Z_1) \tag{A-79}$$

For example the mutual resistance between two x-directed conductors, one located in region 3 and the other located in region 1 is

$$RM(x,y,z,X_1,Y_1,Z_1) = \frac{VX_{31}(x,y,z)}{I}$$

$$= \frac{S_{31}H(x,y,z)}{I}$$

$$= \frac{1}{8\pi L_1 L(\sigma_1+\sigma_2)} \sum_{i=0}^{\infty} (K_{12}K_{32})^i$$

$$\{\sqrt{(x-X_1-L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2} - \sqrt{(x-X_1+L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}$$

$$- \sqrt{(x-X_1-L-L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2} + \sqrt{(x-X_1+L-L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}$$

$$- (x-X_1-L+L_1)\ \ell n[x-X_1-L+L_1 + \sqrt{(x-X_1-L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]$$

$$+ (x-X_1+L+L_1)\ \ell n[x-X_1+L+L_1 + \sqrt{(x-X_1+L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]$$

$$+ (x-X_1-L-L_1)\ \ell n[x-X_1-L-L_1 + \sqrt{(x-X_1-L-L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]$$

$$- (x-X_1+L-L_1)\ \ell n[x-X_1+L-L_1 + \sqrt{(x-X_1+L-L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]\} \qquad \text{(A-80)}$$

The self resistance of a conductor is defined as the self potential of the conductor divided by the current leaving the conductor. As demonstrated before, the conductor self potential is the same as the mutual potential evaluated at $x-X_1 = 0$, $y-Y_1 = a$, $z-Z_1 = 0$. The self resistance is evaluated as RM evaluated at $x-X_1 = 0$, $y-Y_1 = a$, $z-Z_1 = 0$, where a is the radius of the conductor.

A.11 MUTUAL AND SELF CAPACITANCE

To calculate the capacitance between underground conductors in electrical contact with the earth, we determine the voltage in terms of charge on the conductors.

Analysis of voltage due to a charge distribution is similar to the analysis for evaluation of the voltage induced by current distributions. In this case the voltage is induced by the charge on the conductor rather than the current. As in previous sections, we can apply the integrals of Green's Functions' solutions, Laplace's Equation, superposition and method of moments to obtain the voltage induced by a point charge. As an example of this process the voltage at a point in region 1 due to a point charge source in region 2 is given by

$$V = \frac{Q_p}{4\pi\epsilon_2} \int_0^{\infty} \phi(k) J_0(kr) e^{kz} dk \qquad z \leq D \tag{A-81}$$

which is obtained by simply replacing I_p with Q_p and σ by ε in Equation (A-8) due to the fact that the source is a point charge instead of a point current.

With the same reasoning let

$$K'_{12} \triangleq \frac{\epsilon_1 - \epsilon_2}{\epsilon_1 + \epsilon_2} \tag{A-82}$$

$$K'_{32} \triangleq \frac{\epsilon_3 - \epsilon_2}{\epsilon_3 + \epsilon_2} \tag{A-83}$$

A sequence of "S" equations can be written for the capacitance case. As an example, the "S_{32}" is written using the form of Equation (A-52) as

$$SC_{32}\{G(x,y,z)\} \triangleq \frac{Q}{4\pi L_1(\epsilon_3+\epsilon_2)} \sum_{i=0}^{\infty} (K'_{12}K'_{32})^i \, G(x-X_1, y-Y_1, z-Z_1)$$

$$- K'_{12} \sum_{i=0}^{\infty} (K'_{12}K'_{32})^i \, G(x-X_1, y-Y_1, z-Z_1-2iD-2D) \tag{A-84}$$

Thirty-six equations for the voltage induced on one conductor due to the charge on another conductor can be developed in exact parallel to the thirty-six equations developed for the voltages induced by current sources. To obtain an equation for the voltage induced by a conductor's own charge (self-potential) Equation (A-77) is combined with Equation (A-84) as was done before.

The thirty-six capacitance equations would be essentially the same as Equations (A-60), (A-61), (A-62), (A-66), (A-67) and (A-68) but using "SC" functions as Equation (A-84) instead of "S" functions as Equation (A-52). All have the general form

$$V(x,y,z,X_1,Y_1,Z_1,Q) = Q\, F'(x,y,z,X_1,Y_1,Z_1) \quad .$$

The voltage is linearly dependent on the charge on the conductor. The mutual capacitance is defined as

$$CM(x,y,z,X_1,Y_1,Z_1) = \frac{V(x,y,z,X_1,Y_1,Z_1)}{Q} \tag{A-85}$$

As an example, the mutual capacitance between two conductors both x-directed and one located in region 1 and the other located in region 3 is given by

$$CM(x,y,z,X_1,Y_1,Z_1) = \frac{VX_{31}(x,y,z)}{Q} = \frac{SC_{31}\ H(x,y,z)}{Q}$$

$$= \frac{1}{8\pi L_1 L(\epsilon_1+\epsilon_2)} \sum_{i=0}^{\infty} (K'_{12}K'_{32}) \Big\{ \sqrt{x-X_1-L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}$$

$$- \sqrt{(x-X_1+L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2} - \sqrt{(x-X_1-L-L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}$$

$$+ \sqrt{(x-X_1+L=L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}$$

$$- (x-X_1-L+L_1)\ \ell n[x-X_1-L+L_1+\sqrt{(x-X_1-L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]$$

$$+ (x-X_1+L+L_1)\ \ell n[x-X_1+L+L_1+\sqrt{(x-X_1+L+L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]$$

$$+ (x-X_1-L-L_1)\ \ell n[x-X_1-L-L_1+\sqrt{(x-X_1-L-L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]$$

$$- (x-X_1+L-L_1)\ \ell n[x-X_1+L-L_1+\sqrt{(x-X_1+L-L_1)^2+(y-Y_1)^2+(z-Z_1-2iD)^2}]\Big\} \tag{A-86}$$

The self capacitance can be determined using the mutual capacitance equations evaluated at $x-X_1 = 0$, $y-Y_1 = a$, $z-Z_1 = 0$.

Appendix I.B

NETWORK ANALYSIS

The purpose of this appendix is to outline in detail the analysis method used for the computation of currents and voltages at any point of the representative system shown in Figure 2.1. The approach taken is to develop an equivalent circuit representation of the physical system and to apply network analysis techniques.

To demonstrate certain salient features of the methodology the system under consideration is illustrated again in Figure B.1. The system consists of a substation, an overhead feeder and a section of buried cable. A fault is assumed to exist at distance x from the feeder end of the cable. It is assumed that normal load current is negligible with respect to the fault current. Consequently, only one phase of the overhead line which feeds the URD cable is included. An overhead ground wire is included and is assumed to have a copper connection to the substation ground mat at one end and to the cable shield at the other end. Also represented are m ground rods assumed to be connected to the cable shield.

The ground mat represented is assumed to be electrically connected to the neutral of the secondary of the substation transformer (grounded Y secondary). It should be emphasized that the assumptions regarding the continuity of the neutral system are not restrictive. Assume, for example, an open neutral exists at a specific location (because of corrosion or simple lack of overhead ground wire). This case can be simulated by inserting a very high resistence at an appropriate place in the neutral circuit.

The cable, the substation ground mat, and the ground rods are embedded in earth. For analysis purposes the earth embedded structures of the system are partitioned into n+2m+4 segments as outlined below.

The cable is partitioned into n segments as it is shown in Figure B.1. The segmentation is such that the fault falls at the boundary of two adjacent segments, i and i+1, $1 \leq i \leq n-1$.

The segments of the cable are numbered 1 through n. Each ground rod is segmented into two segments. These segments are numbered n+1 through n+2m, where m is the number of ground rods. Finally, the grounding grid of the substation is assumed

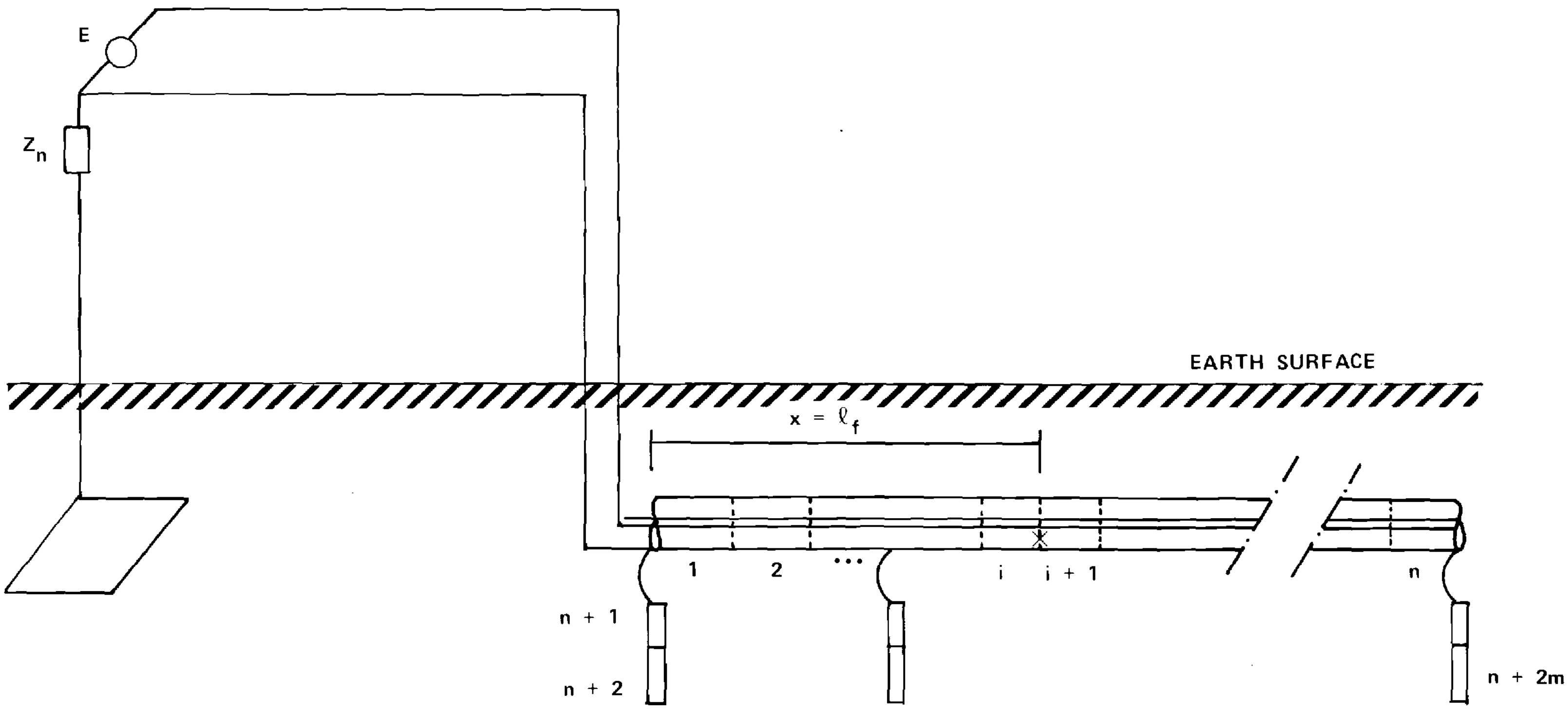


FIGURE B.1 URD CABLE CONFIGURATION WITH m GROUND RODS AND SUBSTATION GROUND MAT to be type A, as defined in IEEE Std-80. It is segmented into four segments numbered n+2m+1 through n+2m+4.

Consider the n+2m+4 earth embedded segments. The outside surface of each segment which is in direct contact with the soil is a cylindrical surface. In general this surface will be at some voltage V and, therefore, current will flow into earth as in Figure B.2a. Using assumptions

(a) constant current density flow from the outer surface of a segment into earth

(b) constant voltage over the outer surface of a segment,

the following matrix equation can be developed:

$$Z_{LAP}\ I = V \qquad \text{(B-1)}$$

where

Z_{LAP} is an (n+2m+4)x(n+2m+4) matrix resulting from the numerical solution of Laplace's equation,

I is an (n+2m+4)x1 vector of the total currents flowing into earth from each segment described above,

V is an (n+2m+4)x1 vector of the average voltages of each segment.

In general, the average voltage V_i of segment i is not a constant but depends on the external circuit, the geometry and electrical properties of the cable, induction phenomena occurring inside the cable, soil parameter, etc. In order to account for all these effects, a rather detailed equivalent circuit model for the cable as well as the feeder is developed from which the voltages V of each segment can be computed.

Specifically, the analysis consists of three steps:

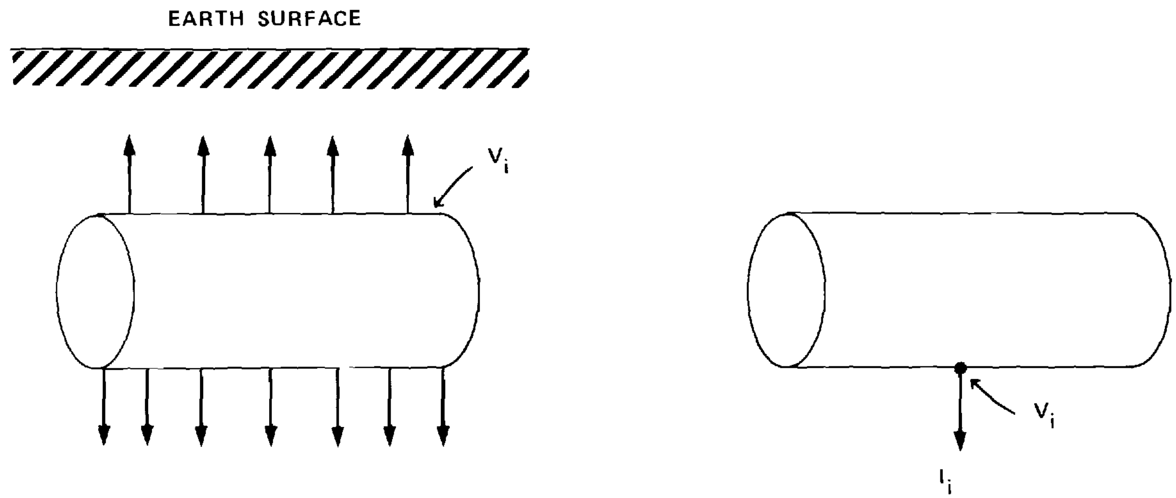
<u>step 1</u>: An equivalent circuit representation of the earth is developed.

<u>step 2</u>: An equivalent circuit representation of the substation, overhead distribution line, and cable is developed.

<u>step 3</u>: The interconnected equivalent circuits from steps 1 and 2 are analyzed using the modified nodal analysis.

After completion of step 3, all currents and voltages are known for the system, including the earth leakage currents, I. Knowledge of the leakage currents, I, allows the computation of earth potentials (and therefore touch and step potentials) with the procedure outlined in Appendix I.A.

In this appendix steps 1, 2, and 3, are outlined in detail.



(a) (b)

FIGURE B.2 a) PHYSICAL SYSTEM OF ONE SEGMENT
b) SIMPLIFIED ASSUMPTION FOR ANALYSIS PURPOSES

B.1 EQUIVALENT CIRCUIT REPRESENTATION OF EARTH

To arrive at an equivalent circuit representation of the earth, two simplifying assumptions are introduced:

(a) The potential of the middle point of segment i is V_i.

(b) The current I_i which flows from the surface of segment i into earth is concentrated at the middle point of segment i (Figure B.2b).

These assumptions, while considerably simplifying the computation, do not introduce appreciable error in the accuracy of the computed voltages and currents.

The problem of defining an equivalent representation of the earth circuit can now be defined as that of determining a set of network elements connected between the n+2m+4m cable segments and remote earth such that the resulting network satisfies Equation B.1.

The solution to this problem proceeds by first computing $Y_{LAP} = Z_{LAP}^{-1}$. Since Z_{LAP} is a symmetric matrix (Appendix I.A), matrix Y_{LAP} is also symmetric. The entry Y_{ij}, $i \neq j$, of matrix Y_{LAP} equals the negative of the admittance of a network element connected between points i and j. (Note that point i is located on the outer surface of segment i and point j is located on the outer surface of segment j.) Thus this procedure, which is not unique, determines all equivalent circuit elements between any two points i and j, $i \neq j$. The equivalent circuit element connected between i and remote earth is defined as Y_i and is determined as

$$Y_i = \sum_{j=1}^{n+2m+4} Y_{ij} .$$

This procedure will yield the equivalent circuit representation of earth which is illustrated at the lower part of Figure B.3.

B.2 EQUIVALENT CIRCUIT MODEL OF SUBSTATION, OVERHEAD LINE, AND CABLE

a) Substation

The substation is represented by its Thevenin equivalent network as in Figure B.3. The positive and zero sequence impedances at the substation secondary are defined as Z_1 and Z_0 respectively. Substation neutral impedance is defined as Z_n. Note that if there is a copper connection between the neutral and the ground mat, $Z_n = 0$.

In the above substation representation, it is assumed that the positive and negative sequence impedances are equal.

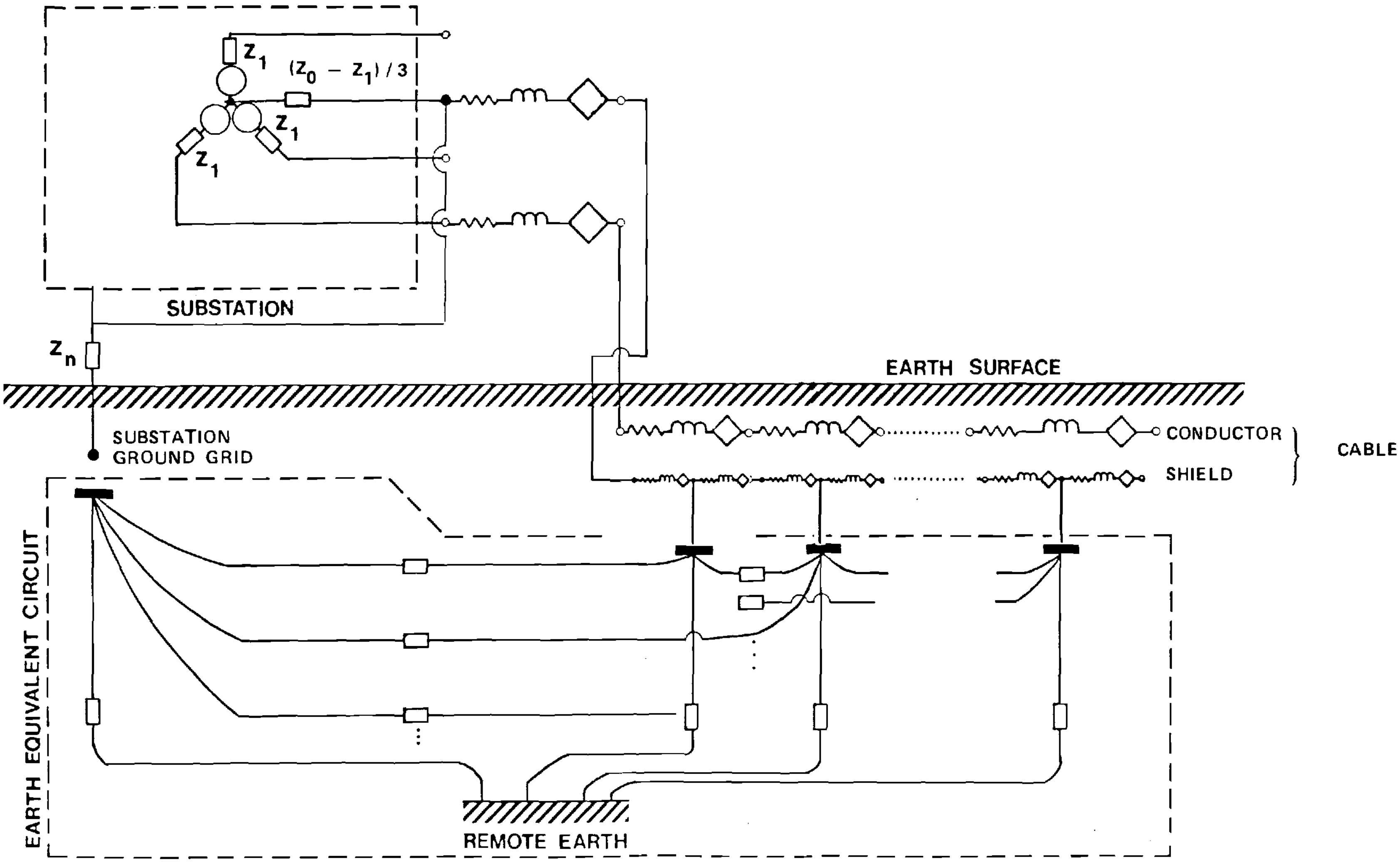


FIGURE B.3 EQUIVALENT CIRCUIT REPRESENTATION OF SUBSTATION, OVERHEAD LINE, SUBSTATION GROUND, AND EARTH.

b) Overhead Line

The overhead distribution line is represented with series resistance, series inductance and magnetic coupling between phase conductors, ground wires, and earth return currents. Thus the transmission line is characterized with the following parameters:

- r_p : series resistance per unit length of phase conductor
- r_g : series resistance per unit length of ground wire
- d_p : GMR of overhead phase conductor
- D : GMD between overhead phase and ground wire
- H : GMD between overhead wires and earth return currents.

These parameters suffice to define voltage drop and induced voltages on the transmission line, using classical transmission line theory.

B.3 EQUIVALENT CIRCUIT MODELS OF BURIED SEGMENTS

There are two types of segments to be modeled:

(1) Ground rod or grounding grid segments

(2) Cable segments.

The models of the above segments are different and are described below.

a) Ground Rod or Grounding Grid Segment

Figure B.2 represents a ground rod or grounding grid segment. It is assumed to be that it is a cylindrical homogeneous conductor. (In reality it may be copperweld, stranded, or combination conductor.) The equivalent circuit of this segment is as in Figure B.4.

In Figure B.4, R_i is the longitudinal resistance of the conductor segment i. The effect of radial resistance may be neglected.

b) Cable Segments

A cable segment is shown in Figure B.5. The cable may or may not have a jacket. The equivalent circuit representation of cable segment is obtained based on the following assumptions:

(1) The voltage on a cross section of the conductor or the shield is constant as indicated in Figure B.5.

(2) Current I_i flows into earth from the middle point of the jacket (or in the absence of jacket from the middle point of the shield) as indicated in Figure B.5.

(3) The power frequency currents I_{ci}, I^-_{ni} and I^+_{ni}, as well as the earth return currents induce voltages on the conductor and shield which can be described by the following approximate relationships

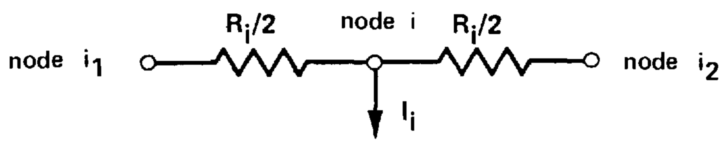


Figure B.4 Equivalent circuit of ground rod or grounding grid segment.

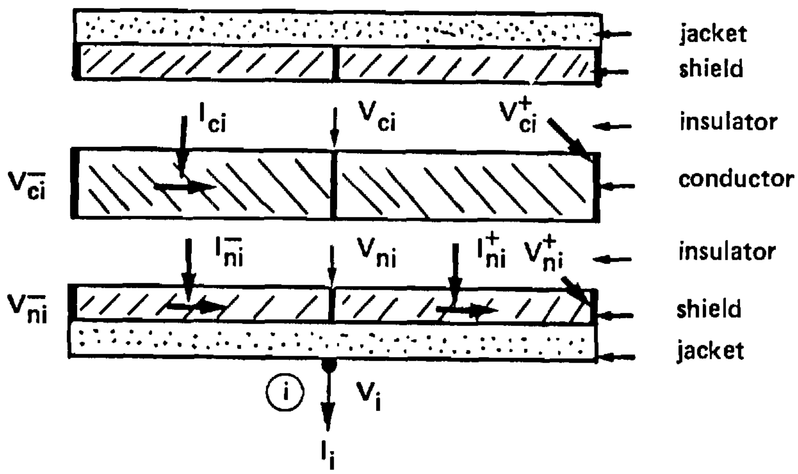


Figure B.5 Cable segment geometry

$$V_c = j\,\frac{\omega\mu\ell}{2\pi}\left(I_c\,\ell n\,\frac{D_e}{d_c} + I_n\,\ell n\,\frac{D_e}{c}\right)$$

$$V_c = j\,\frac{\omega\mu\ell}{2\pi}\left(I_c\,\ell n\,\frac{D_e}{d_c}\quad I_n\,\ell n\,\frac{D_e}{c}\right)$$

$$V_n = j\,\frac{\omega\mu\ell}{2\pi}\,(I_c + I_n)\,\ell n\,\frac{D_e}{c}$$

where:

D_e is a geometric mean distance between the earth return currents and the cable conductor

d_c is the GMR of the cable conductor

c_ℓ is the GMR of the shield (average radius)

ℓ is the length of the section under consideration

(4) Capacitive effects are neglected.

These assumptions result in the equivalent circuit of Figure B.6. Note that the coupling effects are represented with current dependent voltage sources.

B.4 NETWORK ANALYSIS

The individual equivalent circuit representation of the system components, if put together, result in the equivalent system network representation of Figure B.3. A modified nodal analysis technique is applied to solve for voltages and current anywhere in the circuit. This network analysis method is suited to the problem because of the presence of mutual coupling.

B.5 MODIFIED NODAL ANALYSIS

Standard nodal analysis cannot handle voltage sources as well as dependent voltage sources and inductive coupling. In the present case, inductive coupling is present and modeled by current dependent voltage sources. In order to modify standard nodal analysis to this application, the current through each voltage source is introduced as an independent variable. The nodal equations are then expressed in terms of node voltages and the current through the voltage sources. For branches containing voltage sources on additional equation is written relating node voltages and current at that voltage source. These equations, employing compact matrix notations, are given below.

It should be noted that this network problem could be solved using loop analysis methods. However, the modified nodal analysis approach retains certain advantages characteristic of the nodal analysis method. That is, it employs the admittance matrix. This matrix is sparse and thus enables use of sparcity techniques. Due to the dimensionality of the network problem at hand, this property is crucial to obtaining a solution.

B.6 NODE EQUATIONS

a) Node i, Figure B.6

$$\frac{1}{r_{ji}} V_i - \frac{1}{r_{ji}} V_{ni} = -I_i \qquad i = 1,2,\ldots,n \tag{B-2}$$

b) Note i, Figure B.4.

$$\frac{1}{R_i} V_i - \frac{2}{R_i} V_{i_2} = -I_i \qquad i = n+1,\ldots,n+2m+4 \tag{B-3}$$

c) Node ni, Figure B.6.

$$\left(\frac{1}{r_{ji}} + 2y_{ni}\right)V_{ni} - \frac{1}{r_{ji}} V_i - y_{ni} V_{ni}^- - y_{ni} V_{ni}^+ = 0 \tag{B-4}$$

d) Node $ni^{\pm}$ (or $ni^{\mp}$), Figure B.6.

$$(y_{ni}+y_{n(i+1)})V_{ni}^+ - y_{ni}V_{ni} - y_{n(i+1)}V_{n(i+1)}$$
$$- a_{2i}I_{ci} + a_{2(i+1)}I_{c(i+1)} = 0 \tag{B-5}$$

where

$$a_{2i} = \frac{2x_{nci}}{r_{ni}+2x_{nci}}$$

$$y_{ni} = \frac{2}{r_{ni}+2x_{nci}}$$

Note that if $I_{ci} = I_{c(i+1)}$ (which is the usual case) and $a_{2i} = a_{2(i+1)}$, the above equation reduces to

$$4V_{ni}^+ - 2V_{ni} - 2V_{n(i+1)} = 0$$

e) Node ci^+ (or ci^-), Figure B.6.

Note: Node ci is eliminated. Then the node equation for node ci^+ reads:

$$V_{ci}^+ = V_{c(i+1)}^-$$

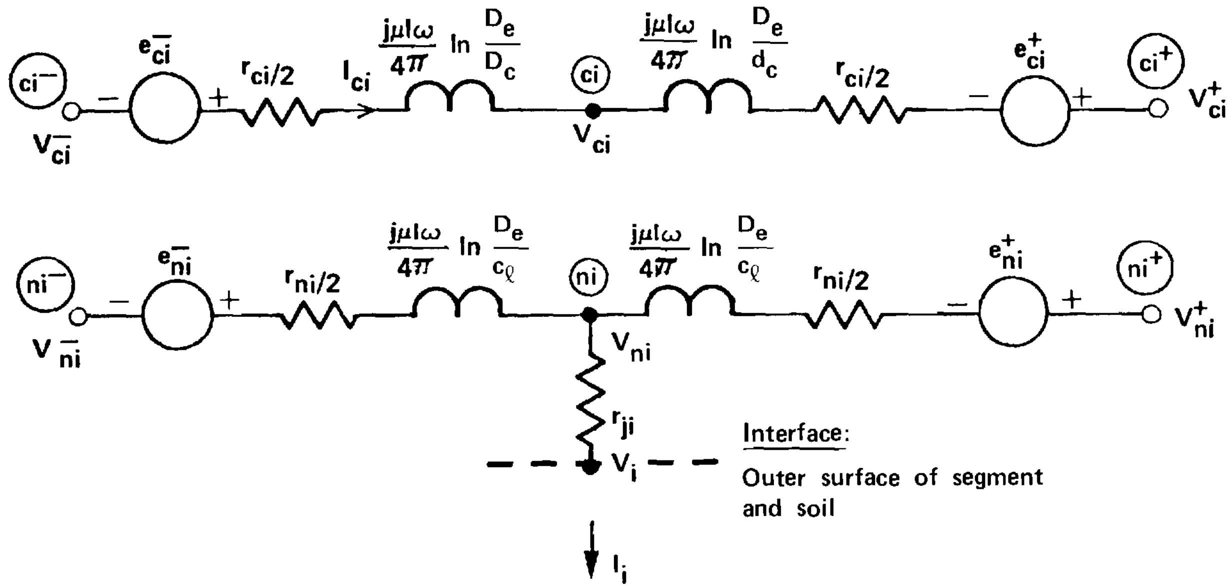


Figure B.6 Equivalent Circuit of a Cable Segment

Explanation of Symbols

r_{ci}	longitudinal resistance of cable conductor
r_{ni}	longitudinal resistance of metallic shield
ℓ	length of the segment
ω	angular power frequency (377 $\sec^{-1}$)
μ	permeability of free space
D_e	geometric mean distance between earth return currents and the cable conductor
c_ℓ	GMR of the shield (average radius)
r_{ji}	radial resistance of the jacket (if cable is not jacketed, $r_{ji} = 0$)

$e_{ci}^- = x_{nci} I_{ni}^-$ $\qquad$ $e_{ci}^+ = x_{nci} I_{ni}^+$

$e_{ni}^- = x_{nci} I_{ci}$ $\qquad$ $e_{ni}^+ = x_{nci} I_{ci}$

$$(y_{ci}+y_{c(i+1)})V^+_{ci} - y_{ci}V^+_{c(i-1)} - y_{c(i+1)}V^+_{c(i+1)} - b_{1i}I^-_{ni} - b_{1i}I^+_{ni} +$$

$$+ b_{1(i+1)}I^-_{n(i+1)} + b_{1(i+1)}I^+_{n(i+1)} = 0 \qquad \text{(B-6)}$$

$$y_{ci} = \frac{1}{r_{ci}+2x_{ei}}$$

$$b_{1i} = \frac{x_{nci}}{r_{ci}+2x_{ei}}$$

$$x_{ei} = j\frac{\omega\mu\ell}{4\pi}\ \ell n\ \frac{D}{d}\ ,$$ ℓ is the length of segment i

In addition, one equation for each branch containing a voltage source may be written as follows:

f) Branch ni^- to ni, Figure B.6.

$$V^-_{ni} - V_{ni} - (\frac{r_{ni}}{2} + x_{nci})I^-_{ni} + x_{nci}I_{ci} = 0 \qquad \text{(B.7)}$$

g) Branch ni to ni^+, Figure B.6.

$$V_{ni} - V^+_{ni} - (\frac{r_{ni}}{2} + x_{nci})I^+_{ni} + x_{nci}I_{ci} = 0 \qquad \text{(B.8)}$$

h) Branch ci^- (or $c(i-1)^+$) to ci^+, Figure B.6

$$V^+_{c(i-1)} - V^+_{ci} - (r_{ci}+2x_{ei})I_{ci} + x_{nci}I^-_{ni} + x_{nci}I^+_{ni} = 0 \qquad \text{(B.9)}$$

It is expedient to write the above equations in a concise matrix form. Define

Vector $V = [V_i]$, $i = 1,2,\ldots,n+2m+4$ as previously (equation (B.1))

Vector V' is the vector of the voltages at nodes ni, ni^+, ci^+, i_1 and i_2

Vector $I = [I_i]$, $i = 1,2,\ldots,n+2m+4$ as previously (equation (B.1))

Vector I' is the vector of currents on the branches (ni^- to ni), (ni to ni^+), and (ci^- to ci^+)

With the above defined vectors, equations (B.2) through (B.9) can be written in the following concise matrix form:

$$\begin{bmatrix} Y & A' & 0 \\ C' & D' & E' \\ 0 & G' & H' \end{bmatrix} \begin{bmatrix} V \\ V' \\ I' \end{bmatrix} = \begin{bmatrix} -I \\ 0 \\ 0 \end{bmatrix} \qquad \text{(B.10)}$$

In addition to the above equation, equation (B.1) relates the voltages V to the currents I and it is cited again:

$$Z_{LAP} I = V \tag{B.1}$$

or $\quad Y_{LAP} V = I$

The problem has thus been reduced in manipulating equations (B.1) and (B.10) in order to obtain the solution for the currents I.

Certain properties of these equations are noteworthy. In equation (B.10), submatrix $\begin{bmatrix} Y & A' \\ C' & D' \end{bmatrix}$ is the usual admittance matrix, if the dependent voltage sources in the equivalent circuit are neglected. Secondly, if it is desired to represent loads supplied by taps along the cable, these loads can be inserted between appropriate nodes. Each load will change only four entries of the admittance matrix. Finally, externally imposed constraints on the source can be accommodated by modifying equations (B.10). These modifications are discussed in the next paragraph. The simultaneous solution of the modified equation (B.10) and (B.1) will yield the solution for the currents.

B.7 SUPPLY SYSTEM MODEL

To illustrate the modification of equations (B.10) because of the externally imposed constraints (supply system), consider the supply system of Figure B.7. If the load on the overhead line is to be neglected, and nodes g and s are defined, (as in the figure), the following equations apply to the supply system:

$$V_s - V_g = E_s \tag{B.11}$$

$$V_s - \bar{V}_{c1} - (Z_1 + \ell_o r_p + j\,\frac{\omega\mu\ell o}{2\pi}\,\ell n\,\frac{H}{d_p})\, I_{c1}$$

$$+ j\,\frac{\omega\mu\ell o}{2\pi}\,\ell n(\frac{H}{D})\, \bar{I}_{n1} = 0 \tag{B.12}$$

$$\frac{3}{Z_0 - Z_1} V_g - \frac{3}{Z_0 - Z_1} V_n + I_{C1} = 0 \tag{B.13}$$

where:

- r_g resistance of overhead ground wire (Ω/m)
- r_p resistance of overhead phase wire (Ω/m)
- ℓ_o length of overhead line (m)
- d_g GMR of ground wire
- d_p GMR of phase wire

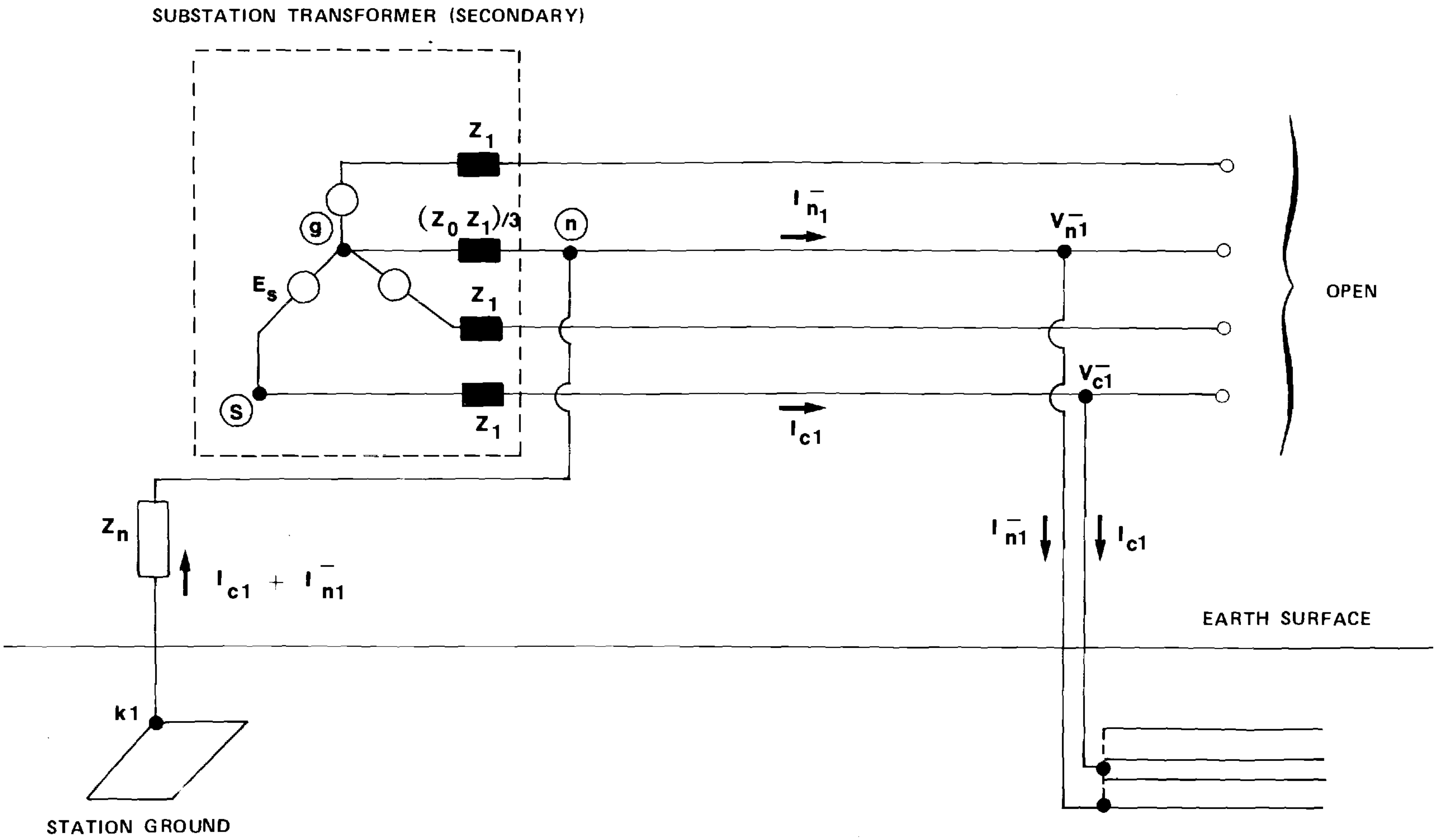


FIGURE B.7 SUPPLY SYSTEM FOR THE URD CABLE

H geometric mean distance of earth return currents from the overhead line

Z_n current limiting impedance

D neutral and phase conductor spacing

Certain comments are pertinent to equations B.11 through B.13. Note that equation B.13 is the modified node equation for node g if the three phase equivalent voltage source of the substation is considered to be open circuited. Also note that equation B.12 is branch equation for branch ($s-\bar{c1}$). Therefore, equations B.12 and B.13 will be included in equations B.10, if the procedure of the previous paragraph is followed and the three phase voltage source at the substation is replaced with an open circuit. To account for the voltage source, however, the node equation for node S is replaced with equation B.11.

From the previous discussion the steps for forming the network equations are:

<u>Step 1</u>: Consider the equivalent circuit representation of the substation, overhead line, and cable. (In Figure B.3 everything except the earth equivalent circuit.)

<u>Step 2</u>: Replace the three phase voltage source at the substation with an open circuit.

<u>Step 3</u>: Write the modified nodal equations for resulting network. The result will be equations B.10.

<u>Step 4</u>: Replace (in B.10) the modified nodal equation for node S with equation B.11. The resulting equations will be:

$$\begin{bmatrix} Y & A & O \\ C & D & E \\ O & G & H \end{bmatrix} \begin{bmatrix} V \\ V' \\ I' \end{bmatrix} = \begin{bmatrix} -I \\ e_s E_s \\ O \end{bmatrix} \tag{B.14}$$

where

e_s is a vector whose entries are all zero except the entry corresponding to node s. This entry equals 1.0. E_s is the source voltage.

The simultaneous solution of Equation B.1 and B.14 will yield the currents I.

B.8 SOLUTION FOR CURRENTS I

The matrix equation (B.14) can be written as:

$$YV + AV' = -I \tag{B.15}$$

$$CV + DV' + EI' = e_s E_s \tag{B.16}$$

$$GV' + HI' = 0 \tag{B.17}$$

The last equation can be solved for I':

$$I' = -H^{-1}GV' \tag{B.18}$$

Substituted into (B.16), we obtain

$$CV + DV' - EH^{-1}GV' = e_sE_s$$

The above equation may be solved for V'

$$V' = (D-EH^{-1}G)^{-1}e_sE_s - (D-EH^{-1}G)^{-1}CV \tag{B.19}$$

Substitute V' from B.19 and V from B.1 into equation (B.15) to obtain

$$(Y - A(D-EH^{-1}G)^{-1}C)Z_{LAP} + I_{id}\ I = -A(D-EH^{-1}G)^{-1}e_sE_s$$

where I_{id} is the (n+2m+4) x (n+2m+4) identity matrix. And, finally,

$$I = -\ I_{id} + (Y - A(D-EH^{-1}G)^{-1}C)Z_{LAP}\ ^{-1}A(D-EH^{-1}G)^{-1}e_sE_s \tag{B.20}$$

The above equation yields the currents flowing into earth from the segmented URD cable system. Back substitution into equation (B.1) will yield the voltages V:

$$V = Z_{LAP}I \quad .$$

In addition, the voltages V' and the currents I' may be obtained with a back substitution in Equations (B.19) and (B.18).

Appendix I.C

COMPUTATION OF THE AT-FAULT VOLTAGE

The procedure for the computation of the at-fault voltage is outlined. This computation is made on the basis of the reduced equivalent circuit of Figure C.1, consisting of a substation feeding the URD cable through a certain length of overhead line. In the analysis to follow, load currents are neglected. A fault (phase to neutral) is assumed to exist at a certain length from the supply end of the cable, ℓ_f.

If the impedance of the substation grounding system is Z_{gg}, the equivalent earth impedance between substation ground and fault cable (at the fault is Z_{gc}, and the equivalent impedance to remote earth of the cable (reduced at the fault) is Z_{cc}, then the circuit representation of the system can be constructed as in Figure C.1.

In Figure C.1, Z_1 is the positive sequence impedance of the substation, Z_0 is the zero sequence impedance of the substation, and Z_n a current limiting impedance inserted between secondary neutral and grounding mat. The point of departure for the computation of the at-fault voltage is the Kirchoff voltage law around loops 1 and 2. (Loops 1 and 2 are defined as follows: Loop 1: overhead feeder phase conductor-cable conductor-fault-cable shield-overhead feeder ground wire-substation. Loop 2: overhead feeder phase conductor-cable conductor-fault-earth-substation ground-substation.)

$$E = I_p \,[(Z_0 + 2Z_1)/3.0 + \ell_o r_p + \ell_f r_c + j\alpha\ell_o \ell n(\frac{D}{d_p})$$

$$+ j\alpha\ell_f \ell n(\frac{C_\ell}{d_c})] + I_g \,[\ell_o r_g + \ell_f r_s + j\alpha\ell_o \ell n(\frac{D}{d_g})]$$

$$E = I_p[\frac{Z_0+2Z_1}{3} + Z_n + \ell_o r_p + \ell_f r_c + j\alpha\ell_o \ell n(\frac{H}{d_p}) + j\alpha\ell_f \ell n(\frac{D_e}{d_c})$$

$$+ R_f] - I_g[R_f + Z_n + j\alpha\ell_o \ell n(\frac{H}{D}) + j\alpha\ell_f \ell n\,(\frac{D_e}{C})]$$

where

Z_1: positive sequence impedance at substation secondary

Z_0: zero sequence impedance at substation secondary

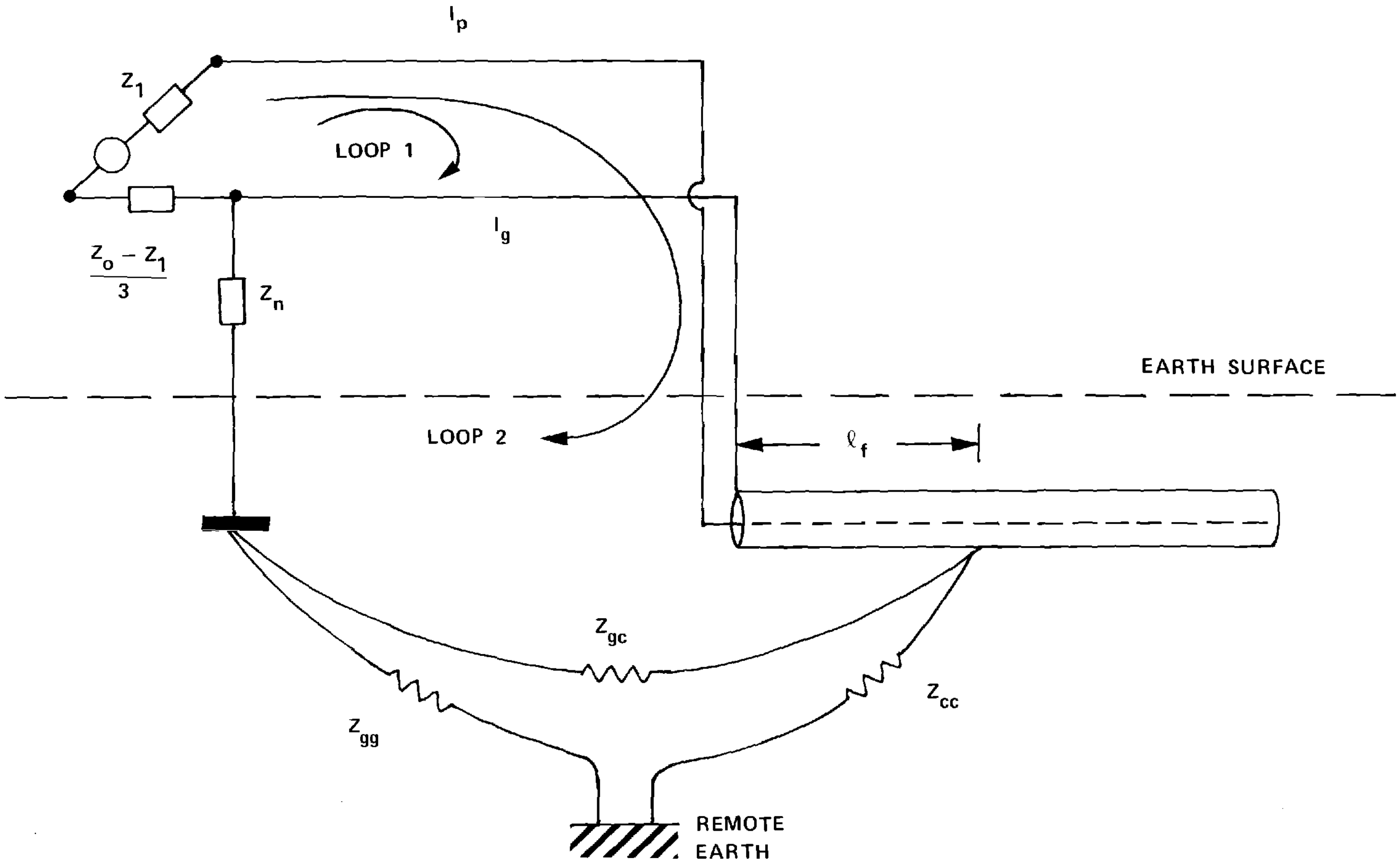


FIGURE C.1 EQUIVALENT CIRCUIT REPRESENTATION OF URD CABLE SYSTEM FOR AT FAULT VOLTAGE COMPUTATION PURPOSES

Z_n: a current limiting impedance connected between substation transformer secondary neutral and substation ground mat.

ℓ_o: length of overhead feeder line

ℓ_f: position of fault on cable from feeding point

r_p: resistance per unit length of overhead line phase conductor

r_c: resistance per unit length of cable conductor

r_s: resistance per unit length of cable shield

r_g: resistance per unit length of overhead line ground wire

d_p: GMR of overhead line phase conductor

d_g: GMR of overhead line ground wire

D : GMD between phase conductor and ground wire of overhead line

c_ℓ: average radius of cable shield

d_c: GMR of cable conductor

H : GMD between overhead wires and earth return current. It is recommended to use twice the average height of the overhead line.

D_e: GMR of the earth return current. The value D_e = 1 yard is suggested.

and

α : .000001256f or .00466f, f frequency in Hz. The first value is to be employed if the metric system of units is used. The second value is to be employed if the English units are used.

It should be noted that it is very difficult to accurately compute the quantities H and D_e. Such a computation would require determination of current flow distribution inside earth and their interaction with the magnetic field resulting from all currents. Fortunately, however, the effects of the geometric mean distances H and D_e are not significant. Figure C.2 illustrates the dependence of the at-fault voltage on the GMR of the earth return currents. For a wide variation of D_e, the at-fault voltage variation is practically negligible. For this reason, the recommended values for the parameters H and D_e can be used safely.

In order to cast the equations in compact form, let

$$a = \frac{2Z_1+Z_0}{3} + \ell_o r_p + \ell_f r_c + j\alpha\ell_o \ln\frac{D}{d_p} + j\alpha\ell_f \ln\frac{C}{d_c}$$

$$b = \ell_o r_g + \ell_f r_s + j\alpha\ell_o \ln\frac{D}{d_g}$$

$$c' = \frac{2Z_1+Z_0}{3} + Z_n + \ell_o r_p + \ell_f r_c + j\alpha\ell_o \ln\left(\frac{H}{d_p}\right) + j\alpha\ell_f \ln\left(\frac{D_e}{d_c}\right)$$

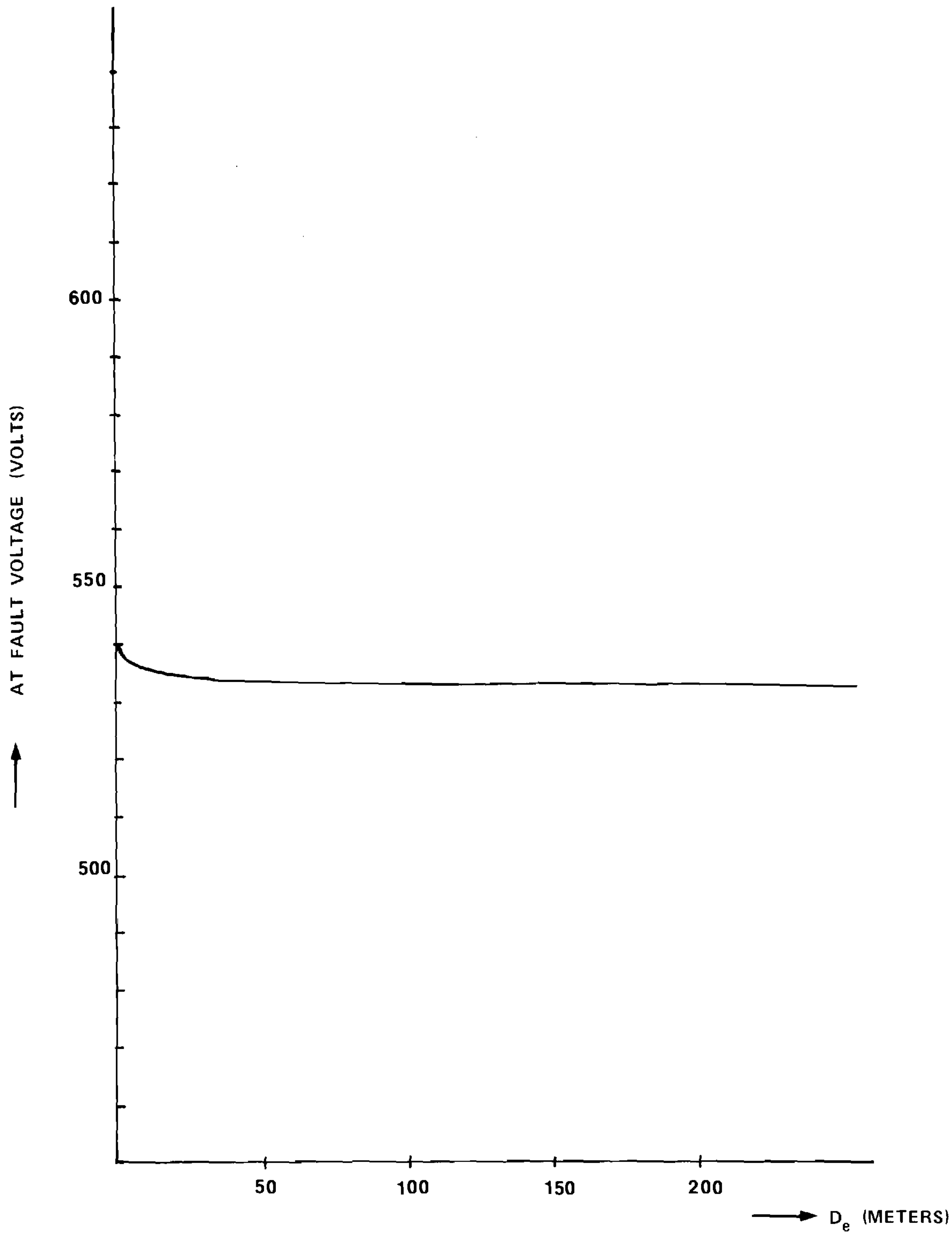


FIGURE C.2 AT FAULT VOLTAGE AS A FUNCTION OF GMR OF EARTH RETURN CURRENTS

$$d' = Z_n + j\alpha\ell_o \ell n \left(\frac{H}{D}\right) + j \quad {}_f \; n \left(\frac{D_e}{c}\right)$$

Then

$$E = aI_p + bI_g$$

$$E = (c'+R_f)I_p - (d'+R_f)I_g$$

Solution of above equations will yield:

$$I_p = \frac{b+d'+R_F}{a(d'+R_F)+b(c'+R_F)} E$$

$$I_g = \frac{c'+R_F-a}{a(d'+R_F)+b(c'+R_F)} E$$

The at-fault voltage V_F is:

$$V_F = I_{e1}Z_{cc}$$

Note

$$I_{e1} + I_{e2} = I_p - I_g$$

and

$$Z_{gc}I_{e2} + (Z_{cc} + Z_{gg})\, I_{e1}$$

$$I_{e1} = \frac{Z_{gc}}{Z_{cc}+Z_{gg}+Z_{gc}} (I_p - I_g) = \frac{Z_{gc}}{(Z_{cc}+Z_{gg}+Z_{gc})} \frac{b+a-c'+d'}{a(d'+R_F)+(c'+R_F)} E$$

And finally, the at-fault voltage is defined by

$$V_F = \frac{Z_{cc}Z_{gc}}{(Z_{cc}+Z_{gg}+Z_{gc})} \frac{b+a-c'+d'}{a(d'+R_F)+b(c'+R_F)} E$$

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Volume 2: Handbook and Graphical Data

EPRI EL-1605
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Project 797-2
Final Report
June 1981

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Underground Distribution
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Graphical and Tabular Results of Computer Simulation of Faulted URD Cables
Volume 2: Handbook and Graphical Data

EL-1605, Volume 2
Research Project 797-2

Final Report, June 1981

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ABSTRACT

A method for computing shield potentials of underground residential distribution (URD) cable shield potentials is presented. Earth potentials in the vicinity of the buried cable are also computed. The method utilizes a numerical solution of Laplace's equation to account for earth currents, and a modified nodal analysis method to account for conductor and shield currents as well as inductive coupling in the underground cable system. A computer program has been developed capable of analyzing long lengths of URD cable together with existing ground rods, faults, open neutrals, feeding substation, and substation grounds. The system analyzed corresponds to practical URD cable distribution systems. Extensive simulation of various URD cable systems in various soil environments has been performed and the results tabulated. The simulation program employed and the applicable theory is documented in Volume 1 of this report. In Volume 2 of the report, the simulation results are documented in handbook form. From these graphs and tables, "touch and step" potentials on the earth surface can be determined for various cable types, network connections, and soil types.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report is a follow-on to RP797-1, which described a general computer program to calculate "touch and step" potentials of faulted underground residential distribution (URD) cables. The computer program, entitled BCAB, permits the simulation of URD cable faults for a wide variety of cables, soils, and excitation parameters. Although the BCAB program is a very valuable analytic tool, it requires approximately 30 complex input parameters for each case studied. RP797-2 extends the usefulness of the BCAB program by expanding the program and by computer simulation. It also resulted in a handbook of curves and graphs from which "touch and step" potentials may be determined for a wide variety of faulted URD cable conditions.

PROJECT OBJECTIVE

The purpose of this project was to modify the BCAB program and use the computer to develop appropriate curves and charts that define the fault behavior of URD cables for a wide class of cables, impedances, and soil conductivity values.

PROJECT RESULTS

The results of this project are presented in two volumes. Volume 1 describes in detail the expanded simulation program used to generate the handbook data. The expanded program can be employed for special problems not covered by the handbook. Volume 2 is an engineer's handbook from which "touch and step" potentials may be determined, using curves and graphs, for a wide variety of URD cable fault conditions.

T. J. Kendrew, Project Manager
Electrical Systems Division

CONTENTS

ILLUSTRATIONS

TABLES

SECTION II.1

HANDBOOK INTRODUCTION

1.1 GENERAL

This volume is a handbook of computer generated data for the estimation of step and touch potentials in the vicinity of faulted URD cables. The handbook is intended to be essentially self-contained. However, the theory and general approach to computation of these data is contained in Volume I of this report, and the user may find reference to that volume useful in dealing with specific unusual situations.

The volume is organized into three parts. The introduction provides a summary description of data, the model upon which it is based and the general approach to utilization of the data. Section 2 provides a detailed users guide outlining the preliminary data and calculation required, data entry procedures, etc. Detailed examples are given. The data themselves are contained in Appendices II.A and II.B.

1.2 DATA DESCRIPTION

Appendices II.A and II.B include data from which the touch and step potentials in the vicinity of the faulted underground cable can be computed. Voltages are normalized to the at-fault voltage (the voltage elevation of the cable shield at the fault). Thus, in order to utilize the data of the present handbook, the at-fault voltage for the system under study must be computed. Then an appropriate entry to the handbook will allow the computation of actual touch and step potentials expected for the system.

Certain simplifications and approximations are involved in the above procedure. These approximations are necessary in order to extend the generality of the computer results. Otherwise, because of the multiplicity of the parameters involved, it would be impossible to tabulate results in manageable volume. On the other hand, the approximation involved in separating the computation of the at-fault voltage and the computation of the normalized touch and step potentials can be justified on the following basis.

(a) Touch and step voltages are very nearly proportional to the at-fault voltage (or cable shield voltage)

(b) At-fault voltage is largely dependent on electrical circuit parameters and soil parameters.

(c) The soil parameters may be reduced to equivalent circuit parameters which, together with the electrical parameters of the system under study, enable computation of at-fault voltage.

(d) The equivalent earth circuit (soil) parameters given as data in the appendices are strongly dependent on only four parameters--cable type, non concentric neutral/semiconducting or insulated, cable grounding, soil resistivities and fault location.

The implications of the above with regard to data formats and data utilization can be assessed with reference to Figure 1.1 which shows a typical data page from Appendix II.A and Figure 1.2 which shows a simplified equivalent circuit. The data format on Figure 1.1 shows touch and step potentials at three locations along the cable, normalized to at-fault voltage. Also given are equivalent earth impedance from the point of fault. These impedance values correspond, for the particular situation represented by the plot, to the impedances on Figure 1.2. By knowing the source voltage and the electrical impedances of the feeder circuit and cable, the absolute value of the at-fault voltage can be readily calculated using an equation described subsequently. With the at-fault voltage determined, the absolute values of step and touch potentials can be obtained by multiplying the normalized value from the plot by the at-fault voltage. Thus, the data on Figure 1.1 are employed twice, once to determine equivalent earth impedances to compute at-fault voltage and once to determine step and touch potentials.

The fact that the at-fault voltage and the step and touch potential determinations are separated enables application of the data to a wide range of feeder configurations and cable designs. For example, the data of Figure 1.1 is applicable to the class of cables with either bare neutral or semiconducting jacket buried in soil of uniform conductivity of .01 ℧/m with grounds rods at approximately 300 foot intervals. Differences in cable parameters such as extent of neutral (full, half, etc.) conductor size, etc., are reflected in the at-fault voltage calculation.

It should be noted that the step and touch potentials at point x along the cable given in the data are defined as follows:

Touch potentials: potential difference between the cable neutral at point x and the earth surface immediately above the cable.

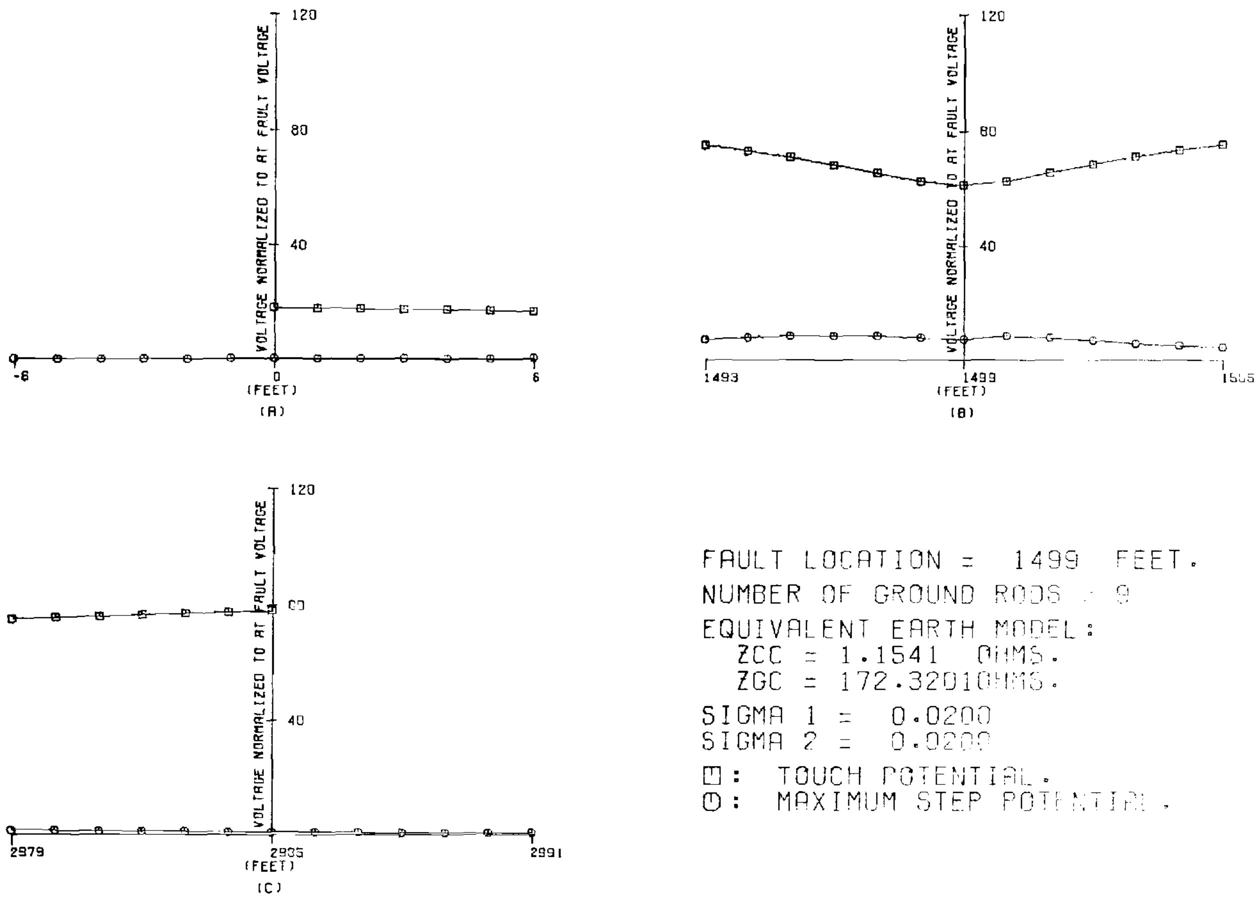


FIGURE 1.1 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

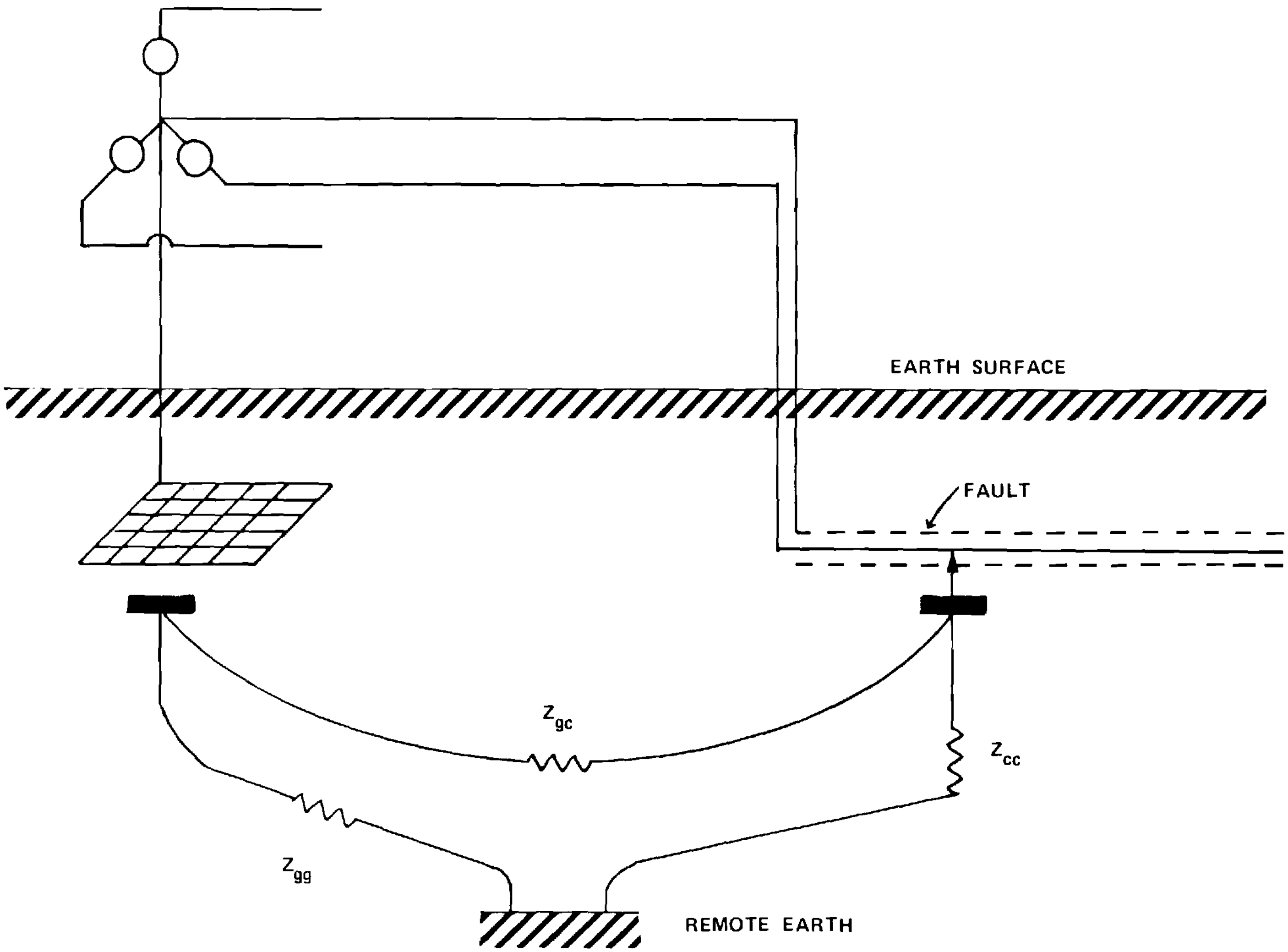


FIGURE 1.2 EQUIVALENT EARTH CIRCUIT FOR AT FAULT VOLTAGE COMPUTATION

Step potentials: maximum potential difference between any two points on the earth surface in the region of point x separated by three feet. A line orthogonal to the cable passing through x and extending ± 6 feet is taken as the reference. Potentials at all points three feet distant from points in this line are calculated and the maximum potential difference is determined.

The above definition of step potential is motivated by the fact that the maximum step potential is not necessarily in a direction either normal to or along the cable and may not be with reference to a point immediately above the point x on the cable.

1.3 SYSTEM DESCRIPTION

The system model which has been used in deriving the data for this handbook is depicted in Figure 1.3. A section of buried cable is supplied by an overhead feeder from a substation. A simple substation grounding system is represented. A two layer earth model is employed. The cable is grounded through regularly spaced ground rods. Results are provided for three fault locations along the cable.

A thorough discussion of the effects of the various parameters of the model on the computed results is provided in Volume I and this report. This discussion indicates the limitations and flexibility of the model. The following sections which define handbook utilization procedures and give illustrative examples will indicate the procedures for adapting the model and the data to specific situations. For additional information the reader is referred to Volume I.

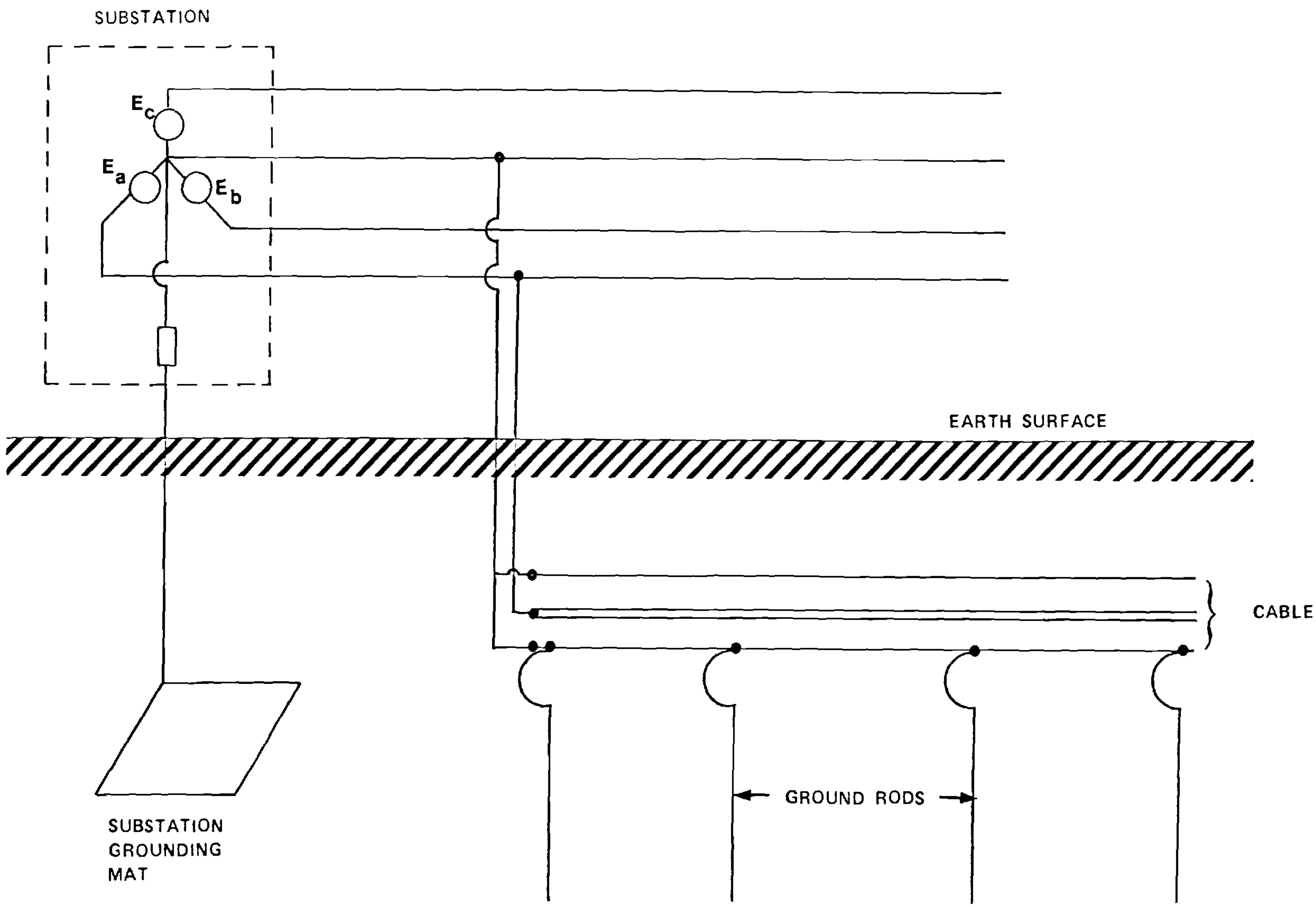


FIGURE 1.3 URD CABLE SYSTEM

SECTION II.2

HANDBOOK UTILIZATION PROCEDURES

2.1 DATA IDENTIFICATION

As outlined in the previous section, the handbook data is used to determine equivalent earth impedances for the at-fault voltage calculation and to determine step and touch potentials. It is, of course, necessary to first identify the applicable data. This will require identifying specific parameters of the system under study and then entering the handbook data to define the applicable figure.

The major subdivision of data has to do with the cable type. Insulating jacket cable data appears in Appendix II.A. Data for semi-conducting jacket and bare concentric neutral cable is given in Appendix II.B. Cable burial depth is a second subdivision of the data. Data for four burial depths is provided. The user should select the depth closest to that utilized for this cable.

Application of ground rods is another data classification. For bare/semi-conducting cable, data is provided for ground rods equally spaced along the cable and for the case of no ground rods. For insulating jacket cable, data is provided for no ground rods and for equally spaced ground rods of two different lengths, eight feet and sixteen feet.

For each of the situations outlined above, data is provided for a range of soil conductivities, both for uniform and two layer soils. The range of data provided is expected to span actual conductivities encountered in practice. However, specific measured values for a given system may not be represented and the closest applicable data should be selected. For each soil condition, data is provided for each of three fault locations, near either end of the cable section and near the center.

Table 2.1 summarizes the data utilization procedure by defining specific steps to be followed. Subsequent paragraphs define these steps explicitly.

2.2 REQUIRED USER SUPPLIED PARAMETERS

The user must define the parameters of the system to be studied. For this purpose, steps 1 through 6 of Table 2.1 should be followed. With the exception of

Table 2.1

HANDBOOK UTILIZATION PROCEDURE

Step 1: Identify supply substation, feeder and URD cable to be studied.

Step 2: Obtain an estimate of soil parameters

0 - 3' earth conductivity, σ_2

3' - ∞ earth conductivity, σ_1

Step 3: Define substation parameters

R_s: substation ground resistance

Z_1: positive and negative sequence impedance

Z_0: zero-sequence impedance

E: supply voltage

Z_n: neutral grounding impedance

Step 4: Define feeder parameters:

r_p: phase conductor resistance per mile

d_p: phase conductor GMR

r_g: ground wire resistance per mile

d_g: ground wire GMR

D: GMC between phase conductor and ground wire

h: average height

ℓ_0: feeder length

Step 5: Define cable parameters:

r_c: conductor resistance per mile

r_s: shield resistance per mile

d_c: conductor GMR

c_ℓ: shield average radius

σ_j,t: conductivity and thickness of jacket

d_b: burial depth

ℓ: cable length

Step 6: Define fault location ℓ_f, and total length of ground rods, ℓ_g.

Table 2.1 (continued)

Step 7: Identify the applicable figure from the appendices and estimate approximate earth equivalent circuit for at-fault voltage

Step 8: Compute the at-fault voltage. This step involves the utilization of an explicit formula.

Step 9: Use computer results to compute touch and step potentials.

soil conductivities and fault location, all other parameters can be obtained from tables and standard substation data. For the estimation of soil conductivities (or resistivities), the procedures outlined in IEEE Std. 81-1962, "IEEE Recommended Guide for Measuring Ground Resistance and Potential Gradients in the Earth", are applicable. Finally, the location of the fault is to be decided by the user. Steps 1-6 will result in data common to all subsequent application. At this point all necessary information for entry to the data is known. Certain preliminary computations are required before the tabulated results of this report can be directly utilized. These computations are described in the next section.

2.3 PRELIMINARY CALCULATIONS

The tabulated touch and step potentials in this report are normalized with the at-fault voltage. Thus in order to utilize the table one needs to compute the at-fault voltage for the case under consideration. In Volume I of this report, the determinant parameters of the at-fault voltage were discussed qualitatively. In this section a step-by-step procedure is described for the computation of the at-fault voltage.

There are two steps in the determination of the at-fault voltage. The first step involves the determination of an equivalent circuit representation for the presence of the earth. The data of this handbook can be directly utilized for this purpose. In the second step, the at-fault voltage is computed with the aid of an explicit formula.

2.4 EQUIVALENT NETWORK REPRESENTATION OF EARTH

The presence of the earth is modeled as an equivalent circuit with three equivalent resistances as in Figure 1.2:

- An equivalent resistance from the faulted cable to remote earth, Z_{cc}
- An equivalent resistance from the substation grounding system to remote earth, Z_{gg}, and
- An equivalent transfer resistance between the substation grounding system and the faulted cable, Z_{gc}.

The equivalent resistance from the substation ground system to remote earth, Z_{gg}, can be computed with procedures described in IEEE Std-80. The other two equivalent resistances Z_{gc}, and Z_{cc} can be defined with the aid of the handbook data as follows:

- Select the appropriate figure for the case under consideration.
- Read values ZGC and ZCC from the figure and compute total length of ground rods ℓ_{GG}.
- Make the following adjustments:

$$Z_{gc} = ZGC\ (\ell_o/200m)$$

$$Z^*_{cc} = ZCC\ (914m+\ {}_{GG})/(\ell+\ell_G)$$

where

ℓ_o, ℓ, ℓ_G, ℓ_{GG} are expressed in meters

or

$$Z_{gc} = ZGC\ (\ell_o/656\text{ ft})$$

$$Z_{cc} = ZCC\ (2998\text{ ft} + \ell_{GG})/(\ell+\ell_G)$$

where

ℓ_o, ℓ, ℓ_G, ℓ_{GG} are expressed in feet

ℓ_o: length of overhead feeder

ℓ: length of underground cable

ℓ_G: total length of ground rods for the case under consideration

ℓ_{GG}: total length of ground rods for the case of the selected figure.

2.5 COMPUTATION OF AT-FAULT VOLTAGE

At-fault voltage depends on the external system, feeding substation voltage and sequence impedances as well as earth conductivity. For the purpose of the at-fault voltage computation, the earth is modeled as lumped resistances. The value of these resistances is dependent on earth resistivity. It should be emphasized that earth is a distributed resistance, and its representation as lumped resistances is only an approximation. In the preceding section the user is guided in selecting appropriate values for these lumped resistances if the earth resistivity is known.

The at-fault voltage is defined by the equation

$$V_F = \frac{Z_{cc}Z_{gc}}{Z_{cc}+Z_{gg}+Z_{gc}} \quad \frac{b+a-c'+d'}{a(d'+R_f)+b(c'+R_f)} \tag{2-1}$$

which is derived in Appendix I.C. The earth circuit impedances Z_{cc},Z_{gc}, Z_{gg} have been defined in the previous section. The resistance R_f is defined in terms of these parameters by

$$R_f = \frac{Z_{gc}(Z_{gs}+Z_{cc})}{Z_{gg}+Z_{gc}+Z_{cc}} \tag{2.2}$$

The impedances a, b, c', d', are defined in terms of external circuit parameters as:

$$a = \frac{2Z_1+Z_0}{3} + \ell_o r_p + \ell_f r_c + j\alpha\ell_o \ \ell n \frac{D}{d_p} + j\alpha\ell_f \ \ell n \frac{C_\ell}{d_c}$$

$$b = \ell_o r_g + \ell_f r_s + j\alpha\ell_o \ \ell n \frac{D}{d_g}$$

$$c' = \frac{2Z_1+Z_0}{3} + Z_n + \ell_o r_p + \ell_f r_c + j\alpha\ell_o \ \ell n \left(\frac{H}{d_p}\right) + j\alpha\ell_f \ \ell n \left(\frac{D_e}{d_c}\right)$$

$$d' = Z_n + j\alpha\ell_o \ \ell n \left(\frac{H}{D}\right) + j\alpha\ell_f \ \ell n \left(\frac{D_e}{c}\right)$$

where

Z_1: positive sequence impedance at substation secondary

Z_0: zero sequence impedance at substation secondary

Z_n: a current limiting impedance connected between substation transformer secondary neutral and substation ground mat.

ℓ_o: length of overhead feeder line

ℓ_f: position of fault on cable from feeding point

r_p: resistance per unit length of overhead line phase conductor

r_c: resistance per unit length of cable conductor

r_s: resistance per unit length of cable shield

r_g: resistance per unit length of overhead line ground wire

d_p: GMR of overhead line phase conductor

d_g: GMR of overhead line ground wire

D : GMD between phase conductor and ground wire of overhead line

c_ℓ: average radius of cable shield

d_c: GMR of cable conductor

H : GMD between overhead wires and earth return current. It is recommended to use twice the average height of the overhead line.

D_e: GMR of the earth return current. The value D_e = 1 yard is suggested.

and

α: .000001256f or .00466f, f frequency in Hz. The first value is to be employed if the metric system of units is used. The second value is to be employed if the English units are used. Table 2.2 is a guide for correct usage of units.

2.6 HANDBOOK ENTRY PROCEDURE AND COMPUTATION OF ACTUAL TOUCH AND STEP POTENTIALS

The cable jacket type will determine the family of curves to be used.

- If jacket is insulating, Appendix II.A is to be entered.
- If cable is bare of jacketed with semiconducting material, Appendix II.B is to be entered.

Next use the specified values for nominal burial depth, nominal earth resistivity, fault location and length of ground rods to isolate curves of step and touch potential at the vicinity of the cable.

Table 2.2.

GUIDE TO CORRECT USE OF UNITS

Variable	Metric System	English System
α	.000001256f	.00466f
f	Hertz	Hertz
Z_1	ohms	ohms
Z_0	ohms	ohms
Z_n	ohms	ohms
R_f	ohms	ohms
ℓ_o	meter	mile
ℓ_f	meter	mile
r_p	ohm/meter	ohm/mile
r_c	ohm/meter	ohm/mile
r_s	ohm/meter	ohm/mile
r_g	ohm/meter	ohm/mile
d_p	meter	foot
d_g	meter	foot
D	meter	foot
c_ℓ	meter	foot
d_c	meter	foot
H	meter	foot
D_e	meter	foot

These curves are normalized to at-fault voltage. Multiply the normalized voltage axis by the computed at-fault voltage to obtain the touch and step potential in actual volts for your system.

The tabular work sheet in Table 2.3, is intended to provide a concise and systematic format for collecting the data to calculate at-fault voltage. Note that inductive parameters X_{pp}, X_{gg}, X_{cc}, X can be calculated as indicated or determined from tables. Table 2.4 provides a work sheet for actually performing the calculation. In this table, the first row defines the parameters and the numerical values are to be entered in the second row. The plus and minus signs in the subsequent rows define the combinations of parameter values to compute parameter a,b,c',d'. A blank entry indicates that the corresponding parameter does not enter the calculation.

It is again emphasized that the calculation of at-fault voltage involves two types of parameters, earth parameters and external circuit parameters. For a given cable type, burial depth, soil parameters, ground rod configuration and fault location, the earth parameters are determined from the handbook data and are fixed. The external circuit parameters are independently specified, and the same earth circuit parameters are applicable for a range of connected circuits. The examples included at the end of this section will help to clarify this point.

Special Case: Corroded or Lack of System Neutral

The computer generated data of this handbook may be used to compute touch and step voltages near URD faulted cable systems whose neutral has been corroded or the feeder lacks ground wire. The major characteristic of these cases is that all the fault current returns through the earth. This case can be approximated with the model of this report if it is assumed that the series resistance of the feeder ground wiring is a very large number, for example 1000 Ω. All other computations and utilization of data should follow the procedure described in this manual.

2.7 EXAMPLES

Several example problems are described in detail in order to define explicitly the handbook utilization procedures.

Case A: Bare Neutral Without Ground Rods

A 2,625 foot long, 15 KV, 4/0, concentric neutral bare cable is connected to a substation 1,312 feet away. Assume there are no ground rods along the cable. Compute the maximum touch and step voltages in the event of a short circuit

Table 2.3.

DATA COLLECTION WORK SHEET

A.	**Substation Parameters**	
R_s:	ground resistance	______
Z_{gg}:	positive sequence impedance	______
Z_0:	zero sequence impedance	______
E :	supply voltage (phase to neutral, rms)	______
Z_n:	neutral grounding impedance	______
B.	**Feeder Circuit Parameters**	
ℓ_o:	feeder length	______
r_p:	phase conductor resistance	______
d_p:	phase conductor GMR	______
X_{PP}:	conductor component of inductive reactance ($.00466f \log_{10} d_p$)	______
r_g:	ground wire resistance	______
d_g:	ground wire GMR	______
X_{GG}:	conductor component of inductive reactance ($.00466f \log_{10} d_g$)	______
D :	GMD between phase conductor and ground wire	______
h :	average conductor height	______
C.	**Cable Parameters**	
r_c:	conductor resistance	______
d_c:	conductor GMR	______

X_{cc}: conductor component of inductive reactance ______

(.00466f $\log_{10} d_c$)

r_s: shield resistance ______

c : average shield radius ______

X_ℓ: reactance of shield (.00466f $\log_{10} \frac{1}{c_\ell}$) ______

ℓ_c: cable length ______

σ_J: jacket conductivity ______

t : jacket thickness ______

ℓ_G: total length of ground rods ______

ℓ_f: fault location ______

d_b: burial depth ______

D. Soil Parameters

σ_2: soil conductivity 0 -3' deep ______

σ_1: soil conductivity 3' -infinity ______

E. Equivalent Earth Circuit Parameters

(from Handbook)

ZGC: equivalent resistance between cable shield and substation ground ______

ZCC: equivalent resistance between cable shield and remote earth ______

ℓ_{GG}: total length of ground rods ______

Corrected Values

$$Z_{gc} = .00152\ \ell_o\ ZGC$$

$$Z_{cc} = \frac{2944+\ell_{GG}}{\ell_c+\ell_G}\ ZCC$$

between conductor and shield 1500 feet away from the source end of the cable. The burial depth is 42 inches and the soil has uniform conductivity .01 mhos/meter.

Solution: The first step is to collect data for the system as described in sections A, B, C, and D in the following data collection work sheet. Note that Sections A, B, C, and D are electrical circuit parameters available as normal system data. The values used for the example system are shown on the data sheets. The entries into Section D require identification of the proper figure in the Appendices. Identify the proper figure by noting that the neutral is bare, there are no ground rods, burial depth is 42 inches, and soil conductivity is uniform at ρ=.01 ohm/meter. Using the table of figures for Appendix B.1, these data define the appropriate curve as being in the group B.106-B.126. Then using the fact that the fault is near the cable center and soil has uniform conductivity yields finally Figure B.118.

Next the quantities a, b, c', and d' are computed, using data from Figure B.118, as entered in Section E of the work sheet (corrected for length variations). The computation work sheet of Table 2.4 can be employed for this calculation.

Use these values in the equation

$$V_F = \frac{Z_{cc}Z_{gc}}{Z_{cc}+Z_{gc}+Z_{gg}} \cdot \frac{b+a+d'-c'}{a(d')+R_f)+b(c'+R_f)} \cdot E$$

to obtain

$$V_F = 35.35-j460.47 \text{ volts}$$

or $\quad V_F = 580$ volts

Then, from Figure B.118 the maximum touch and step voltages are:

$$V_{T\ max} = (0.70)(580) = 406 \text{ volts}$$

$$V_{ST\ max} = (0.10)(580) = 58 \text{ volts}$$

DATA COLLECTION WORK SHEET FOR CASE A

A. Substation Parameters

R_s:	ground resistance	2.3 ohms
Z_{gg}:	positive sequence impedance	.21+j1.48 ohms
Z_0:	zero sequence impedance	.18+j1.42 ohms
E :	supply voltage (phase to neutral, rms)	8660 volts
Z_n:	neutral grounding impedance	0

B. Feeder Circuit Parameters (4/0, ACSR phase, 2/0 ASCR ground wire)

ℓ_o:	feeder length	1312 feet
r_p:	phase conductor resistance	.592 ohms/mile
d_p:	phase conductor GMR	.00814 feet
X_{pp}:	conductor component of inductive reactance (.00466f $\log_{10} d_p$)	.581 ohms/mile
r_g:	ground wire resistance .895 ohms/mile	
d_g:	ground wire GMR	.0051 feet
X_{gg}:	conductor component of inductive reactance (.00466f $\log_{10} d_g$)	.641 ohms/mile
D :	GMD between phase conductor and ground wire	4.5 feet
h :	average conductor height	44 feet

C. Cable Parameters (4/0 single conductor, concentric strand, 15 KV)

r_c:	conductor resistance	.31 ohms/mile
d_c:	conductor GMR	.01666 feet

X_{cc}:	conductor component of inductive reactance ($.00466f \log_{10} d_c$)	.496 ohms/mile
r_s:	shield resistance	2.14 ohms/mile
c_ℓ:	average shield radius	.0437 feet
x_ℓ:	reactance of shield ($x_\ell = .00466f \log_{10}(\frac{1}{c_\ell})$)	.38 ohms/mile
ℓ_c:	cable length	2625 feet
σ_J:	jacket conductivity	.01 mhos/meter
t :	jacket thickness	180 mils
ℓ_G:	total length of ground rods	0
ℓ_f:	fault location	1500 feet
d_b:	burial depth	42 inches

D. Soil Parameters

σ_2:	soil conductivity 0 - 3' deep	.01 mhos/meter
σ_1:	soil conductivity 3' - infinity	.01 mhos/meter

E. Equivalent Earth Circuit Parameters

(from Handbook, Figure B.118)

ZGC:	equivalent resistance between cable shield and substation ground	23.069 ohms
ZCC:	equivalent resistance between cable shield and remote earth	.5585 ohms
ℓ_{GG}:	total length of ground rods	0

Corrected Values

$$Z_{gc} = .00152\, \ell_o \text{ ZGC} = 46\ \Omega$$

$$Z_{cc} = \frac{2994+\ell_{GG}}{\ell_c+\ell_G} \text{ Z}_{cc} = .637\,\Omega$$

TABLE 2.4. PRELIMINARY COMPUTATION WORK SHEET

	$(2Z_1+Z_0)/3$	Z_n	$\ell_o r_p$	$\ell_o r_g$	$\ell_f r_c$	$\ell_f r_s$	$jx^*(D)\ell_o$	$jx^*(\frac{1}{C_p})\ell_f$	$jx^*(H)\ell_o$	$jx^*(D_e)\ell_f$	$jx^*(\frac{1}{d_p})\ell_o$	$jx^*(\frac{1}{d_c})\ell_f$	$jx^*(\frac{1}{d_g})\ell_o$	
a	+		+		+		+	-			+	+		
b				+		+	+						+	
c'	+	+	+		+				+	+	+	+		
d'		+					-	+	+	+				

$x^*(Z) = .00466\ f\ \log_{10}(Z)$

PRELIMINARY COMPUTATION WORK SHEET
(CASE A)

	$(2Z_1+Z_0)/3$	Z_n	$\ell_o r_p$	$\ell_o r_g$	$\ell_f r_c$	$\ell_f r_s$	$jx^*(D)\ell_o$	$jx^*(\frac{1}{C_p})\ell_f$	$jx^*(H)\ell_o$	$jx^*(D_e)\ell_f$	$jx^*(\frac{1}{d_p})\ell_o$	$jx^*(\frac{1}{d_c})\ell_f$	$jx^*(\frac{1}{d_g})\ell_o$	
	.2+j1.46	0	.1471	.2224	.0881	.6080	j.0454	j.1080	j.1351	j.0379	j.1452	j.1409	j.1593	
a	+		+		+		+	–			+	+		.4352+j1.6835
b				+		+	+						+	.8304+j.2047
c'	+	+	+		+				+	+	+	+		.4352+j1.9195
d'		+					-	+	+	+				j.2356

$$x^*(Z) = .00466\ f\ \log_{10}(Z)$$

Case B: Bare Neutral With Ground Rods

A 2,625 foot long, 15 KV, 4/0, concentric neutral bare cable connected to a substation 1,312 feet away. It is grounded with eight ground rods of length ten feet each and equally spaced along the cable. Compute the maximum touch and step voltages in the event of a phase to neutral fault in the conductor and overhead feeder near the source end of the cable. The burial depth is 42 inches and the soil has uniform conductivity .01 mhos/meter.

Solution: Note that for all practical purposes the above fault will yield the same voltage profile as a fault on the cable near the source end. Thus, handbook data for a fault near the source end of the cable is applicable. The procedure for identifying the applicable figure is the same as in Case A except for the inclusion of ground rods. The specifications lead to selection of Figure B.90. Then data are collected as in the following data collection work sheet, and the quantities a, b, c', and d' are computed.

Use equation

$$V_F = \frac{Z_{cc}Z_{gc}}{Z_{cc}+Z_{gc}+Z_{gg}} \cdot \frac{b+a+d'-c'}{a(d')+R_f)+b(c'+R_f)} \cdot E$$

to obtain

$$V_F = 182.5-j133.28 \text{ volts}$$

or

$$V_F = 226 \text{ volts}$$

From Figure B.90 the maximum touch and step voltages are:

$$V_{T\ max} = (0.50)(226) = 113 \text{ volts}$$

$$V_{ST\ max} = (0.16)(226) = 36 \text{ volts}$$

DATA COLLECTION WORK SHEET FOR CASE B

A.	**Substation Parameters**	
R_s:	ground resistance	2.3Ω
Z_{gg}:	positive sequence impedance	$.21+j1.48\Omega$
Z_0:	zero sequence impedance	$.18+j1.42\Omega$
E :	supply voltage (phase to neutral, rms)	8660 volts
Z_n:	neutral grounding impedance	0
B.	**Feeder Circuit Parameters** (4/0, ACSR phase, 2/0 ASCR ground wire)	
ℓ_o:	feeder length	1312 feet
r_p:	phase conductor resistance	.592 ohms/mile
d_p:	phase conductor GMR	.00814 feet
X_{pp}:	conductor component of inductive reactance ($.00466f \log_{10} d_p$)	.581 ohms/mile
r_g:	ground wire resistance	.895 ohms/mile
d_g:	ground wire GMR	.0051 feet
X_{gg}:	conductor component of inductive reactance ($.00466f \log_{10} d_g$)	.641 ohms/mile
D :	GMD between phase conductor and ground wire	4.5 feet
h :	average conductor height	44 feet
C.	**Cable Parameters** (4/0 single conductor, concentric strand, 15 KV)	
r_c:	conductor resistance	.31 ohms/mile
d_c:	conductor GMR	.01666 feet

X_{cc}:	conductor component of inductive reactance ($.00466f \log_{10} d_c$)	.496 ohms/mile
r_s:	shield resistance	2.14 ohms/mile
c_ℓ:	average shield radius	.0437 feet
x_ℓ:	reactance of shield ($.00466f \log_{10} (\frac{1}{c})$)	.38 ohms/mile
ℓ_c:	cable length	2625 feet
σ_J:	jacket conductivity	.01 mhos/meter
t :	jacket thickness	180 mils
ℓ_G:	total length of ground rods	80 feet
ℓ_f:	fault location	0
d_b:	burial depth	42 inches

D. Soil Parameters

σ_2:	soil conductivity 0 - 3' deep	.01 mhos/meter
σ_1:	soil conductivity 3' - to infinity	.01 mhos/meter

E. Equivalent Earth Circuit Parameters

(from Handbook, Figure B.90)

ZGC:	equivalent resistance between cable shield and substation ground	18.8522 ohms
ZCC:	equivalent resistance between cable shield and remote earth	.4448 ohms
ℓ_{GG}:	total length of ground rods	144 feet

Corrected Values

$$Z_{gc} = .00152\ \ell_o\ ZGC = 37.59 \text{ ohms}$$

$$Z_{cc} = \frac{2994+\ell_{GG}}{\ell_c+\ell_G}\ ZCC = .504 \text{ ohms}$$

PRELIMINARY COMPUTATION WORK SHEET
(CASE B)

	$(2Z_1+Z_0)/3$	Z_π	$\ell_o r_p$	$\ell_o r_g$	$\ell_f r_c$	$\ell_f r_s$	$jx^*(D)\ell_o$	$jx^*(\frac{1}{C_p})\ell_f$	$jx^*(H)\ell_o$	$jx^*(D_e)\ell_f$	$jx^*(\frac{1}{d_p})\ell_o$	$jx^*(\frac{1}{d_c})\ell_f$	$jx^*(\frac{1}{d_g})\ell_o$	
	.2+j1.46	0	.1471	.2224	0	0	j.0454	0	j.1351	0	j.1452	0	j.1593	
a	+		+		+		+	-			+	+		.3471+j1.6506
b				+		+	+						+	.2224+j.2047
c'	+	+	+		+				+	+	+	+		.3471+j1.7403
d'		+					-	+	+	+				j.0897

$$x^*(Z) = .00466\ f\ \log_{10}(Z)$$

Case C: Insulating Jacket Without Ground Rods

A 2,625 foot long, 15 KV, 4/0, concentric neutral with insulating jacket cable is connected to a substation 1,312 feet away. Assume there are no ground rods along the cable. Compute the maximum touch and step voltages in the event of a short circuit between conductor and shield 1,500 feet away from the source end of the cable. The burial depth is 42 inches and the soil has uniform conductivity .01 mhos/meter.

Solution: Since the cable has insulating uniform jacket and no ground rods, Figure A.1 gives the applicable data. The computation of the at-fault voltage is similar to previous cases. System data are collected as described in Sections A, B, C, and D in the following data collection work sheet. Next, the quantities a, b, c', and d' are computed.

Use equation

$$V_F = \frac{Z_{cc}Z_{gc}}{Z_{cc}+Z_{gc}+Z_{gg}} \cdot \frac{b+a+d'-c'}{a(d')+R_f)+b(c'+R_f)} \cdot E$$

to obtain

$$V_F = 2327.38-j2146.73 \text{ volts}$$

or

$$V_F = 3166 \text{ volts}$$

From Figure A.1 the maximum touch and step voltages are:

$$V_{T\ max} \cong (1.0)x(3166) = 3166 \text{ volts}$$

$$V_{ST\ max} \cong 0.0$$

DATA COLLECTION WORK SHEET FOR CASE C

A. Substation Parameters

R_s:	ground resistance	2.3 ohms
Z_{gg}:	positive sequence impedance	.21+j1.48 ohms
Z_0:	zero sequence impedance	.18+j1.42 ohms
E :	supply voltage (phase to neutral, rms)	8660 volts
Z_n:	neutral grounding impedance	0

B. Feeder Circuit Parameters (4/0, ACSR phase, 2/0 ASCR ground wire)

ℓ_o:	feeder length	1312 feet
r_p:	phase conductor resistance	.592 ohms/mile
d_p:	phase conductor GMR	.00814 feet
X_{pp}:	conductor component of inductive reactance (.00466f $\log_{10} d_p$)	.581 ohms/mile
r_g:	ground wire resistance	.895 ohms/mile
d_g:	ground wire GMR	.0051 feet
X_{gg}:	conductor component of inductive reactance (.00466f $\log_{10} d_g$)	.641 ohms/mile
D :	GMD between phase conductor and ground wire	4.5 feet
h :	average conductor height	44 feet

C. Cable Parameters (4/0 single conductor, concentric strand, 15 KV)

r_c:	conductor resistance	.31 ohms/mile
d_c:	conductor GMR	.01666 feet
X_{cc}:	conductor component of inductive	

	reactance ($.00466f \log_{10} d_c$)	.496 ohms/mile
r_s:	shield resistance	2.14 ohms/mile
c_ℓ:	average shield radius ($.00466f \log_{10} (\frac{1}{C_\ell})$)	.0437 feet
x_ℓ:	reactance of shield	.38 ohms/mile
ℓ_c:	cable length	2625 feet
σ_J:	jacket conductivity	10^{-10} mhos/meter
t :	jacket thickness	180 mils
ℓ_G:	total length of ground rods	0 feet
ℓ_f:	fault location	1500 feet
d_b:	burial depth	42 inches

D. Soil Parameters

σ_2:	soil conductivity 0 - 3' deep	.01 mhos/meter
σ_1:	soil conductivity 3' - infinity	.01 mhos/meter

E. Equivalent Earth Circuit Parameters

(from Handbook, Figure B.90)

ZGC:	equivalent resistance between cable shield and substation ground	a large number
ZCC:	equivalent resistance between cable shield and remote earth	a large number
ℓ_{GG}:	total length of ground rods	0

Corrected Values

$$Z_{gc} = .00152\, \ell_o \text{ ZGC} = 1{,}000\ \Omega$$

$$Z_{cc} = \frac{2994+\ell_{GG}}{\ell_c+\ell_G} \text{ ZCC} = 100\ \Omega$$

PRELIMINARY COMPUTATION WORK SHEET
(CASE C)

	$(2Z_1+Z_0)/3$	Z_n	$\ell_o r_p$	$\ell_o r_g$	$\ell_f r_c$	$\ell_f r_s$	$j\overset{*}{x}(D)\ell_o$	$j\overset{*}{x}(\frac{1}{C_p})\ell_f$	$j\overset{*}{x}(H)\ell_o$	$j\overset{*}{x}(D_e)\ell_f$	$j\overset{*}{x}(\frac{1}{d_p})\ell_o$	$j\overset{*}{x}(\frac{1}{d_c})\ell_f$	$j\overset{*}{x}(\frac{1}{d_g})\ell_o$	
	.2+j1.46	0	.1471	.2224	.0881	.6080	j.0454	j.1080	j.1351	j.0379	j.1452	j.1409	j.1593	
a	+		+		+		+	-			+	+		.4352+j1.6838
b				+		+	+						+	.8304+j.2047
c'	+	+	+		+				+	+	+	+		.4352+j1.9195
d'		+					-	+	+	+				j.2356

$$x^{*}(Z) = .00466\ f\ \log_{10}(Z)$$

Case D: Insulating Jacket With Ground Rods

A 2,625 foot long, 15 KV, 4/0, concentric neutral with insulating jacket cable is connected to a substation 1,312 feet away. The cable is grounded with eight 14 feet long ground rods, equally spaced. Compute the maximum touch and step voltages in the event of a short circuit between conductor and shield near the source end of the cable. The burial depth is 30 inches and the soil has uniform conductivity .01 mhos/meter.

Solution: The first step is to collect data for the system in Sections A, B, C, and D in the following data collection work sheet. Using ground rod, data, burial depth and soil conductivity leads to Figure A.20 as identifying fault parameters for a fault near the source end. Next, the quantities a, b, c', and d' are computed.

Use equation:

$$V_F = \frac{Z_{cc}Z_{gc}}{Z_{cc}+Z_{gc}+Z_{gg}} \cdot \frac{b+a+d'-c'}{a(d')+R_f)+b(c'+R_f)} \cdot E$$

to obtain

$$V_F = 705.667-j454.99 \text{ volts}$$

or

$$V_F = 839.6 \text{ volts}$$

From Figure A.20 the maximum touch and step voltages are:

$$V_{Tmax} = (0.85)(839.6) = 713.66 \text{ volts}$$

$$V_{STmax} = (.08)(839.6) = 67.2 \text{ volts}$$

DATA COLLECTION WORK SHEET FOR CASE D

A. Substation Parameters

R_s:	ground resistance	2.3 ohms
Z_{gg}:	positive sequence impedance	.21+j1.48 ohms
Z_0:	zero sequence impedance	.18+j1.42 ohms
E :	supply voltage (phase to neutral, rms)	8660 volts
Z_n:	neutral grounding impedance	0

B. Feeder Circuit Parameters (4/0, ACSR phase, 2/0 ASCR ground wire)

ℓ_o:	feeder length	1312 feet
r_p:	phase conductor resistance	.592 ohms/mile
d_p:	phase conductor GMR	.00814 feet
X_{pp}:	conductor component of inductive reactance (.00466f $\log_{10} d_p$)	.581 ohms/mile
r_g:	ground wire resistance	.895 ohms/mile
d_g:	ground wire GMR	.0051 feet
X_{gg}:	conductor component of inductive reactance (.00466f $\log_{10} d_g$)	.641 ohms/mile
D :	GMD between phase conductor and ground wire	4.5 feet
h :	average conductor height	44 feet

C. Cable Parameters (4/0 single conductor, concentric strand, 15 KV)

r_c:	conductor resistance	.31 ohms/mile
d_c:	conductor GMR	.01666 feet
X_{cc}:	conductor component of inductive	

	reactance ($.00466f \log_{10} d_c$)	.496 ohms/mile
r_s:	shield resistance	2.14 ohms/mile
c_ℓ:	average shield radius	.0437 feet
x_ℓ:	reactance of shield ($.00466f \log_{10} (\frac{1}{c_\ell})$)	.38 ohms/mile
ℓ_c:	cable length	2625 feet
σ_J:	jacket conductivity	10^{-10} mhos/meter
t :	jacket thickness	180 mils
ℓ_G:	total length of ground rods	112 feet
f:	fault location	0
d_b:	burial depth	30 inches

D. Soil Parameters

σ_2:	soil conductivity 0 - 3' deep	.01 mhos/meter
σ_1:	soil conductivity 3' - infinity	.01 mhos/meter

E. Equivalent Earth Circuit Parameters

(from Handbook, Figure A.30)

ZGC:	equivalent resistance between cable shield and substation ground	341.4
ZCC:	equivalent resistance between cable shield and remote earth	3.186
ℓ_{GG}:	total length of ground rods	144 feet

Corrected Values

$$Z_{gc} = .00152\ \ell_o\ ZGC = 680 \text{ ohms}$$

$$Z_{cc} = \frac{\ell_{GG}}{\ell_G} ZCC = 4.096 \text{ ohms}$$

PRELIMINARY COMPUTATION WORK SHEET
(CASE D)

	$(2Z_1+Z_0)/3$	Z_n	$\ell_o r_p$	$\ell_o r_g$	$\ell_f r_c$	$\ell_f r_s$	$jx^*(D)\ell_o$	$jx^*(\frac{1}{C_p})\ell_f$	$jx^*(H)\ell_o$	$jx^*(D_e)\ell_f$	$jx^*(\frac{1}{d_p})\ell_o$	$jx^*(\frac{1}{d_c})\ell_f$	$jx^*(\frac{1}{d_g})\ell_o$	
	.2+j1.46	0	.1471	.2224	0	0	j.1045	0	j.3111	0	j.1444	0	j.1593	
a	+		+		+		+	-			+	+		.3471+j1.6506
b				+		+	+						+	.2224+j.2047
c'	+	+	+		+				+	+	+	+		.3471+j1.7403
d'		+					-	+	+	+				j.0897

$$x^*(Z) = .00466\ f\ \log_{10}(Z)$$

Case E: Special Case of Absent Neutral

A 2,625 foot long, 15 KV, 4/0, concentric neutral bare cable is connected to a substation 1,312 feet away with an overhead line. Assume the overhead line has no ground wire. The cable is grounded with eight ground rods of length ten feet each and euqlly spaced. Compute the maximum touch and step voltages in the event of a short circuit between conductor and shield near the source end of the cable. The burial depth is 42 inches and the soil has uniform conductivity .01 mhos/meter.

Solution: The normalized touch and step potentials are illustrated in Figure B.90 (same as for Case B). The at-fault voltage will be different due to the absence of a neutral return. The first step to compute the at-fault voltage is to colelct system data as in Sections A, B, C, and D in the following data collection work sheet. Note that the absence of ground wire is simulated by assuming r_g = 10,000 ohms/mile. Next, the quantities a, b, c', and d' are computed.

Use equation

$$V_F = \frac{Z_{cc} Z_{gc}}{Z_{cc}+Z_{gc}+Z_{gg}} \cdot \frac{b+a+d'-c'}{a(d')+R_f)+b(c'+R_f)} \cdot E$$

to obtain

$$V_F = 1019.7-j600.8 \text{ volts}$$

or

$$V_F = 1183.5 \text{ volts}$$

From Figure B.90 the maximum touch and step voltages are:

$$V_{T\ max} = (0.50)(1183.5) = 592 \text{ volts}$$

$$V_{ST\ max} = (0.16)(1183.5) = 189 \text{ volts}$$

DATA COLLECTION WORK SHEET FOR CASE E

A. Substation Parameters

R_s:	ground resistance	2.3 ohms
Z_{gg}:	positive sequence impedance	.21+j1.48 ohms
Z_0:	zero sequence Impedance	.18+j1.42 ohms
E :	supply voltage (phase to neutral, rms)	8660 volts
Z_n:	neutral grounding impedance	0

B. Feeder Circuit Parameters (4/0, ACSR phase, 2/0 ASCR ground wire)

ℓ_o:	feeder length	1312 feet
r_p:	phase conductor resistance	.592 ohms/mile
d_p:	phase conductor GMR	.00814 feet
X_{pp}:	conductor component of inductive reactance (.00466f $\log_{10} d_p$)	.581 ohms/mile
r_g:	ground wire resistance	10,000 ohms/mile
d_g:	ground wire GMR	.0051 feet
X_{gg}:	conductor component of inductive reactance (.00466f $\log_{10} d_g$)	.641 ohms/mile
D :	GMD between phase conductor and ground wire	4.5 feet
h :	average conductor height	44 feet

C. Cable Parameters (4/0 single conductor, concentric strand, 15 KV)

r_c:	conductor resistance	.31 ohms/mile
d_c:	conductor GMR	.01666 feet
X_{cc}:	conductor component of inductive	

	reactance (.00466f $\log_{10} d_c$)	.496 ohms/mile
r_s:	shield resistance	2.14 ohms/mile
c_ℓ:	average shield radius	.0437 feet
x_ℓ:	reactance of shield (.00466f $\log_{10} (\frac{1}{c_\ell})$)	.38 ohms/mile
ℓ_c:	cable length	2625 feet
σ_J:	jacket conductivity	.01 mhos/meter
t :	jacket thickness	180 mils
ℓ_G:	total length of ground rods	80 feet
ℓ_f:	fault location	0
d_b:	burial depth	42 inches

D. Soil Parameters

σ_2:	soil conductivity 0 - 3' deep	.01 mhos/meter
σ_1:	soil conductivity 3' - infinity	.01 mhos/meter

E. Equivalent Earth Circuit Parameters

(from Handbook, Figure B.90)

ZGC:	equivalent resistance between cable shield and substation ground	18.8522 ohms
ZCC:	equivalent resistance between cable shield and remote earth	.4448 ohms
ℓ_{GG}:	total length of ground rods	144 feet

Corrected Values

$$Z_{gc} = .00152\ \ell_o\ ZGC = 37.59 \text{ ohms}$$

$$Z_{cc} = \frac{2994+\ell_{GG}}{\ell_c+\ell_G}\ ZCC = .5042 \text{ ohms}$$

PRELIMINARY COMPUTATION WORK SHEET
(CASE E)

	$(2Z_1+Z_0)/3$	Z_n	$\ell_o r_p$	$\ell_o r_g$	$\ell_f r_c$	$\ell_f r_s$	$j\overset{*}{x}(D)\ell_o$	$j\overset{*}{x}(\frac{1}{C_p})\ell_f$	$j\overset{*}{x}(H)\ell_o$	$j\overset{*}{x}(D_e)\ell_f$	$j\overset{*}{x}(\frac{1}{d_p})\ell_o$	$j\overset{*}{x}(\frac{1}{d_c})\ell_f$	$j\overset{*}{x}(\frac{1}{d_g})\ell_o$	
	.2+j1.46	0	.1471	.2224	0	0	j.0454	0	j.1351	0	j.1452	0	j.1593	
a	+		+		+		+	-			+	+		.3471+j1.6506
b				+		+	+						+	2485.39+j.2047
c'	+	+	+		+				+	+	+	+		.3471+j1.7403
d'		+					-	+	+	+				j.0897

$x^*(Z) = .00466\ f\ \log_{10}(Z)$

Appendix II.A

GRAPHICAL RESULTS FOR INSULATING JACKET CABLE

This appendix contains all the computer generated data for underground faulted cables with insulating jacket. Figure A.1 shows touch and maximum step potentials for cables with insulating jacket and without ground rods. One curve suffices for all cases because the step potentials are negligible and the maximum touch potential equals approximately the at-fault voltage, for a wide variation of parameters. Figures A.2 through A.121 illustrate data for cables with insulating jacket and ground rods. Table A.1 summarizes the organization of the data for quick reference. Additional information, i.e. soil conductivity, fault location, etc., is given in individual figures.

Table A.1

INSULATING JACKET CABLE

Figure A.1 Touch and Maximum Step Potentials for Insulating Jacket Cable Without Ground Rods

Figures A.2 through A.16
Ground Rods 9 x 8 ft.
Burial Depth 30"

	1	2	Fault: Source End	Fault: Center	Fault: Remote End
A.2	.99	.15	X		
A.3	.1	.1	X		
A.4	.02	.02	X		
A.5	.01	.01	X		
A.6	.01	.0011	X		
A.7	.99	.15		X	
A.8	.1	.1		X	
A.9	.02	.02		X	
A.10	.01	.01		X	
A.11	.01	.0011		X	
A.12	.99	.15			X
A.13	.1	.1			X
A.14	.02	.02			X
A.15	.01	.01			X
A.16	.01	.0011			X

Figures A.17 through A.31
Ground Rods 9 x 16 ft.
Burial Depth 30"

	1	2	Fault: Source End	Fault: Center	Fault: Remote End
A.17	.99	.15	X		
A.18	.1	.1	X		
A.19	.02	.02	X		
A.20	.01	.01	X		
A.21	.01	.0011	X		
A.22	.99	.15		X	
A.23	.1	.1		X	
A.24	.02	.02		X	
A.25	.01	.01		X	
A.26	.01	.0011		X	
A.27	.99	.15			X
A.28	.1	.1			X
A.29	.02	.02			X
A.30	.01	.01			X
A.31	.01	.0011			X

Figures A.32 through A.46
Ground Rods 9 x 8 ft.
Burial Depth 36"

	1	2	Fault: Source End	Center	Remote End
A.32	.99	.15	X		
A.33	.1	.1	X		
A.34	.02	.02	X		
A.35	.01	.01	X		
A.36	.01	.0011	X		
A.37	.99	.15		X	
A.38	.1	.1		X	
A.39	.02	.02		X	
A.40	.01	.01		X	
A.41	.01	.0011		X	
A.42	.99	.15			X
A.43	.1	.1			X
A.44	.02	.02			X
A.45	.01	.01			X
A.46	.01	.0011			X

Figures A.47 through A.61
Ground Rods 9 x 16 ft.
Burial Depth 36"

A.47	.99	.15	X		
A.48	.1	.1	X		
A.49	.02	.02	X		
A.50	.01	.01	X		
A.51	.01	.0011	X		
A.52	.99	.15		X	
A.53	.1	.1		X	
A.54	.02	.02		X	
A.55	.01	.01		X	
A.56	.01	.0011		X	
A.57	.99	.15			X
A.58	.1	.1			X
A.59	.02	.02			X
A.60	.01	.01			X
A.61	.01	.0011			X

Figures A.62 through A.76
Ground Rods 9 x 8 ft.
Burial Depth 42"

	1	2	Fault: Source End	Center	Remote End
A.62	.99	.15	X		
A.63	.1	.1	X		
A.64	.02	.02	X		
A.65	.01	.01	X		
A.66	.01	.0011	X		
A.67	.99	.15		X	
A.68	.1	.1		X	
A.69	.02	.02		X	
A.70	.01	.01		X	
A.71	.01	.0011		X	
A.72	.99	.15			X
A.73	.1	.1			X
A.74	.02	.02			X
A.75	.01	.01			X
A.76	.01	.0011			X

Figures A.77 through A.91
Ground Rods 9 x 16 ft.
Burial Depth 42"

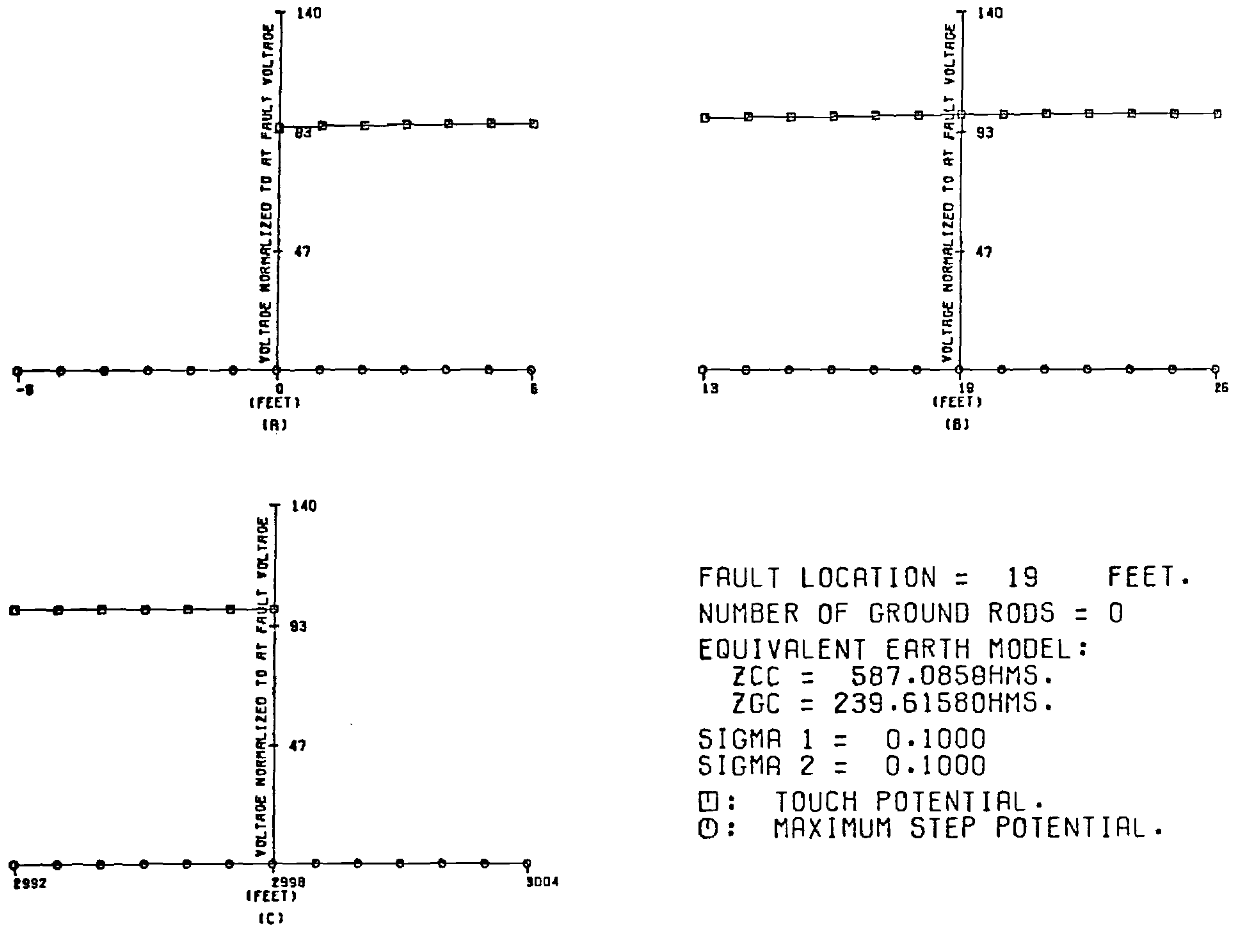
A.77	.99	.15	X		
A.78	.1	.1	X		
A.79	.02	.02	X		
A.80	.01	.01	X		
A.81	.01	.0011	X		
A.82	.99	.15		X	
A.83	.1	.1		X	
A.84	.02	.02		X	
A.85	.01	.01		X	
A.86	.01	.0011		X	
A.87	.99	.15			X
A.88	.1	.1			X
A.89	.02	.02			X
A.90	.01	.01			X
A.91	.01	.0011			X

Figures A.92 through A.106
Ground Rods 9 x 8 ft.
Burial Depth 48"

	1	2	Fault: Source End	Fault: Center	Fault: Remote End
A.92	.99	.15	X		
A.93	.1	.1	X		
A.94	.02	.02	X		
A.95	.01	.01	X		
A.96	.01	.0011	X		
A.97	.99	.15		X	
A.98	.1	.1		X	
A.99	.02	.02		X	
A.100	.01	.01		X	
A.101	.01	.0011		X	
A.102	.99	.15			X
A.103	.1	.1			X
A.104	.02	.02			X
A.105	.01	.01			X
A.106	.01	.0011			X

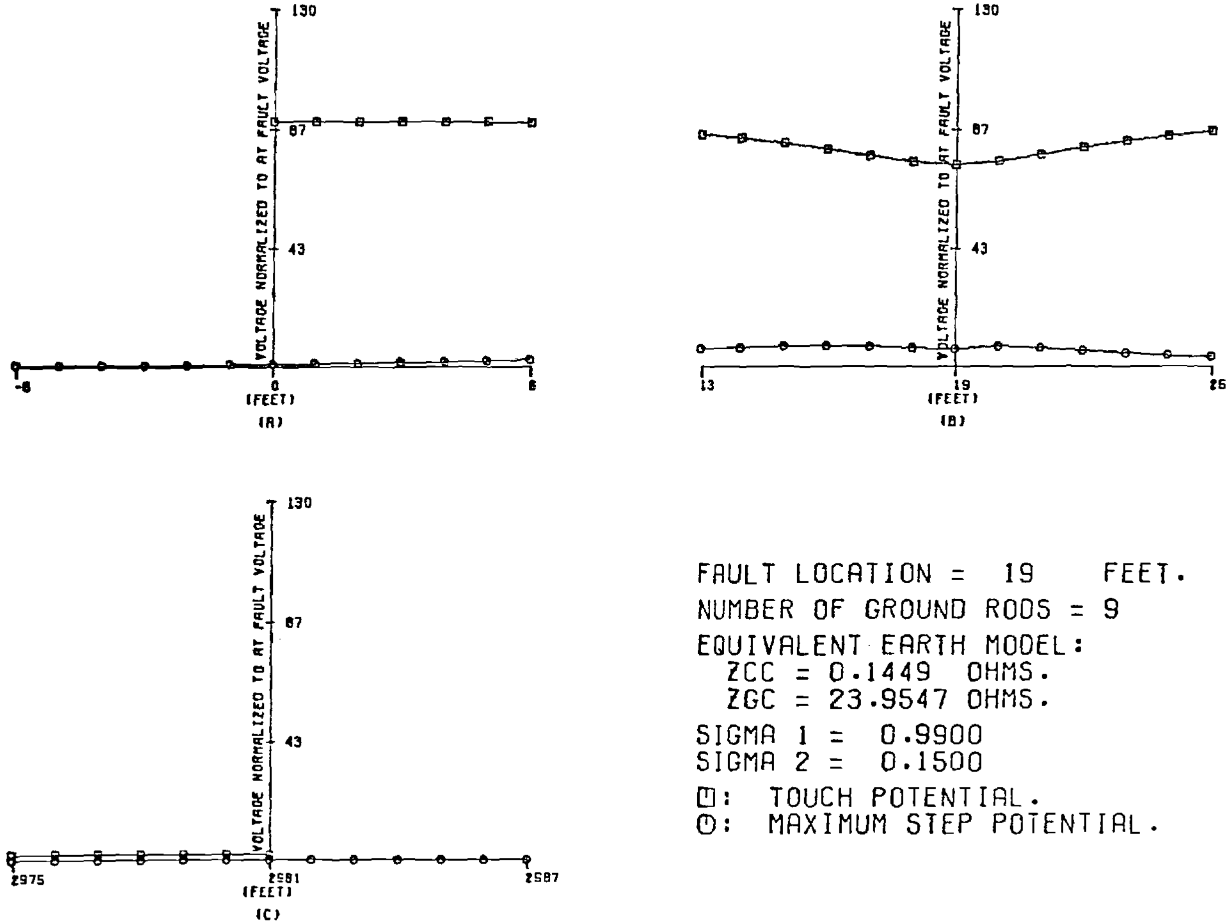
Figures A.107 through A.121
Ground Rods 9 x 16 ft.
Burial Depth 48"

	1	2	Fault: Source End	Fault: Center	Fault: Remote End
A.107	.99	.15	X		
A.108	.1	.1	X		
A.109	.02	.02	X		
A.110	.01	.01	X		
A.111	.01	.0011	X		
A.112	.99	.15		X	
A.113	.1	.1		X	
A.114	.02	.02		X	
A.115	.01	.01		X	
A.116	.01	.0011		X	
A.117	.99	.15			X
A.118	.1	.1			X
A.119	.02	.02			X
A.120	.01	.01			X
A.121	.01	.0011			X



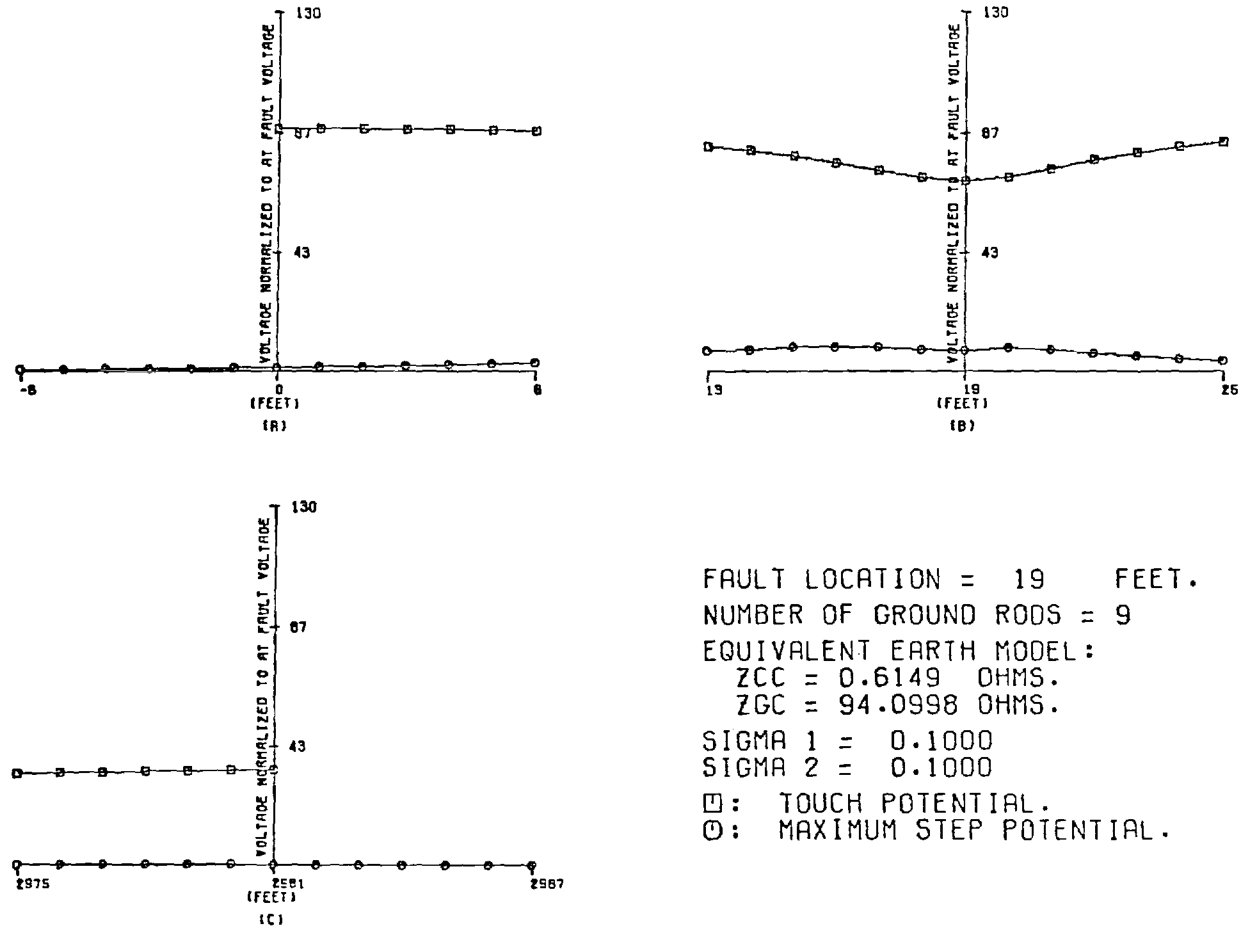
FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 587.085OHMS.
ZGC = 239.6158OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.1. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1449 OHMS.
ZGC = 23.9547 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.2. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.6149 OHMS.
ZGC = 94.0998 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.3. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

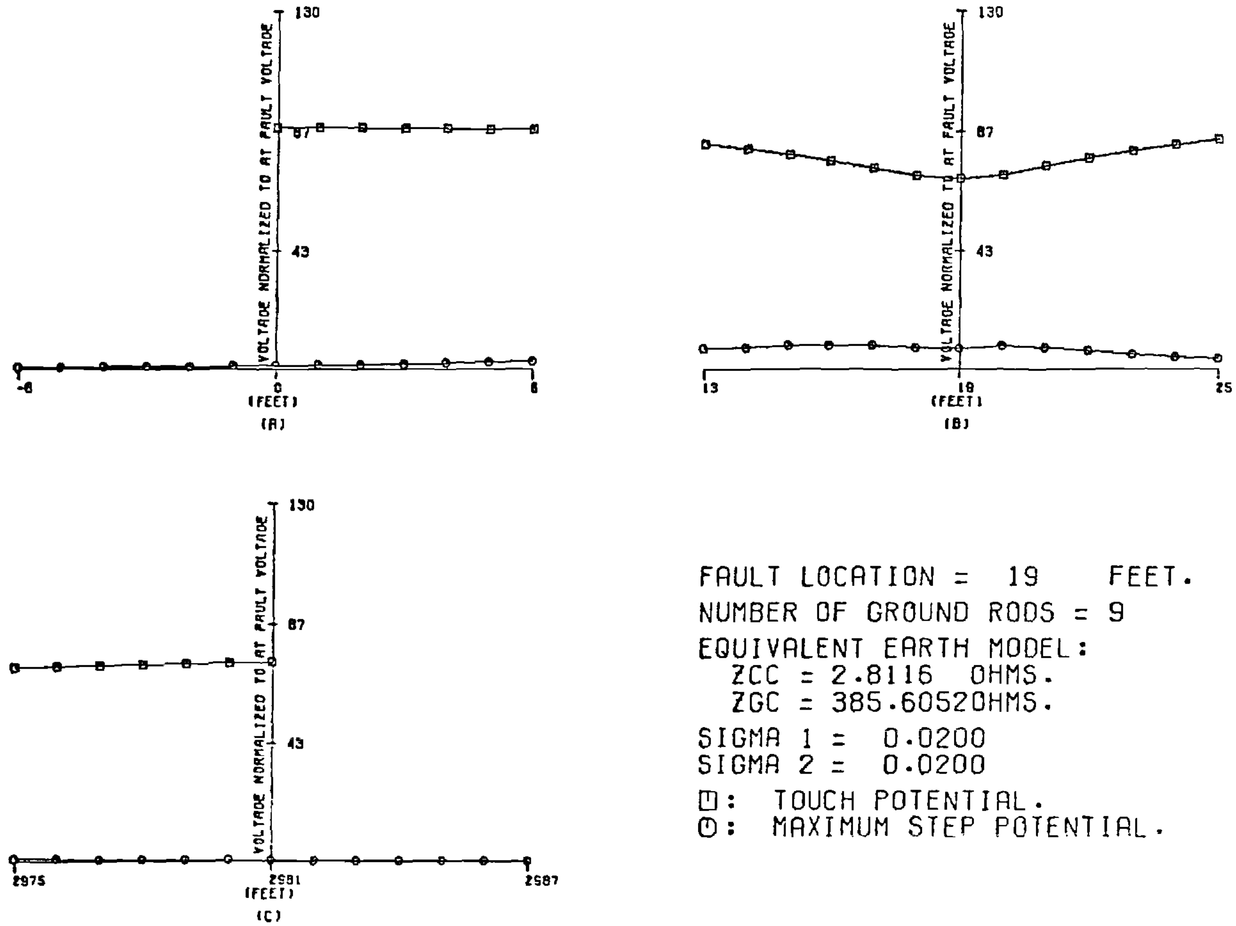


FIGURE A.4. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

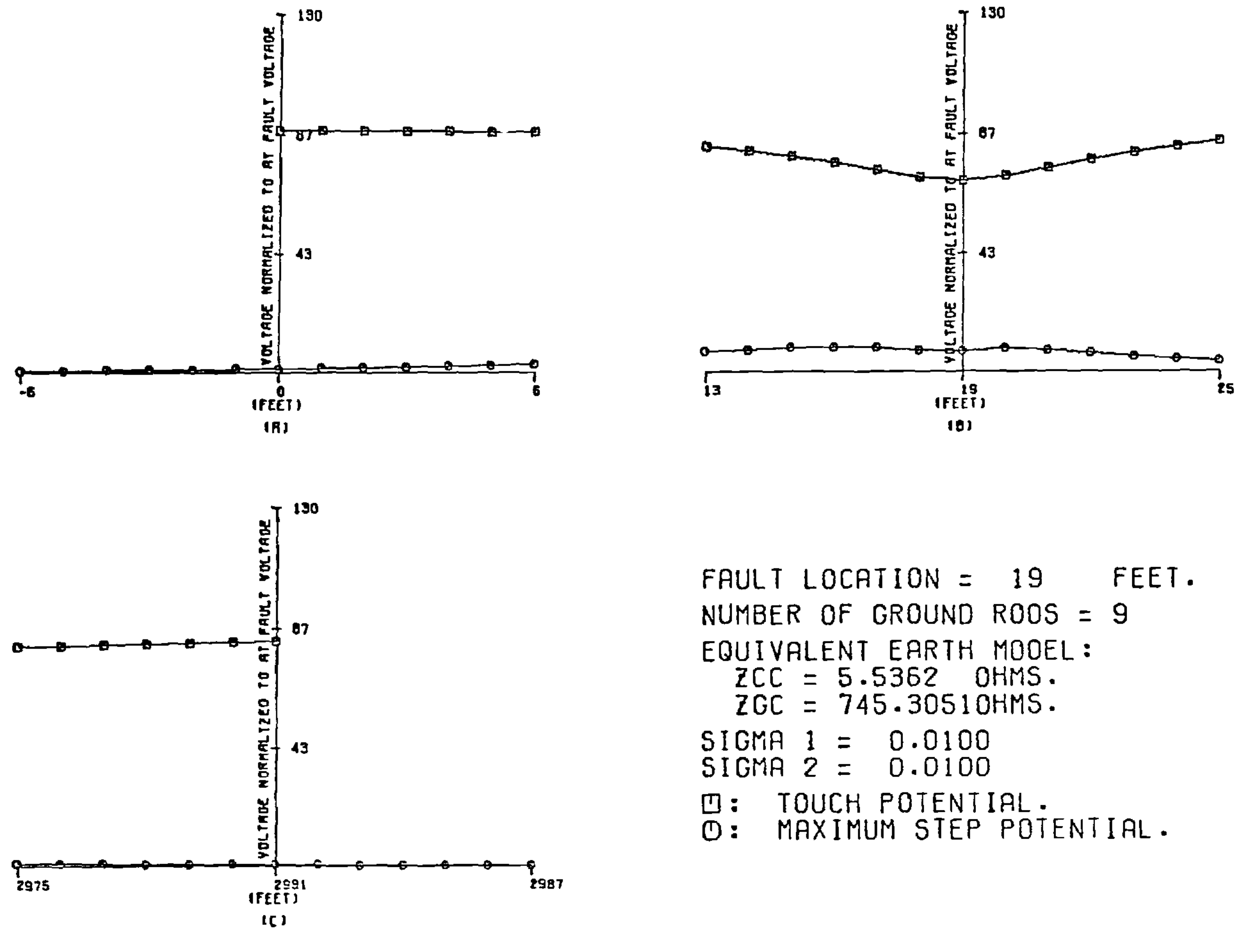


FIGURE A.5. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

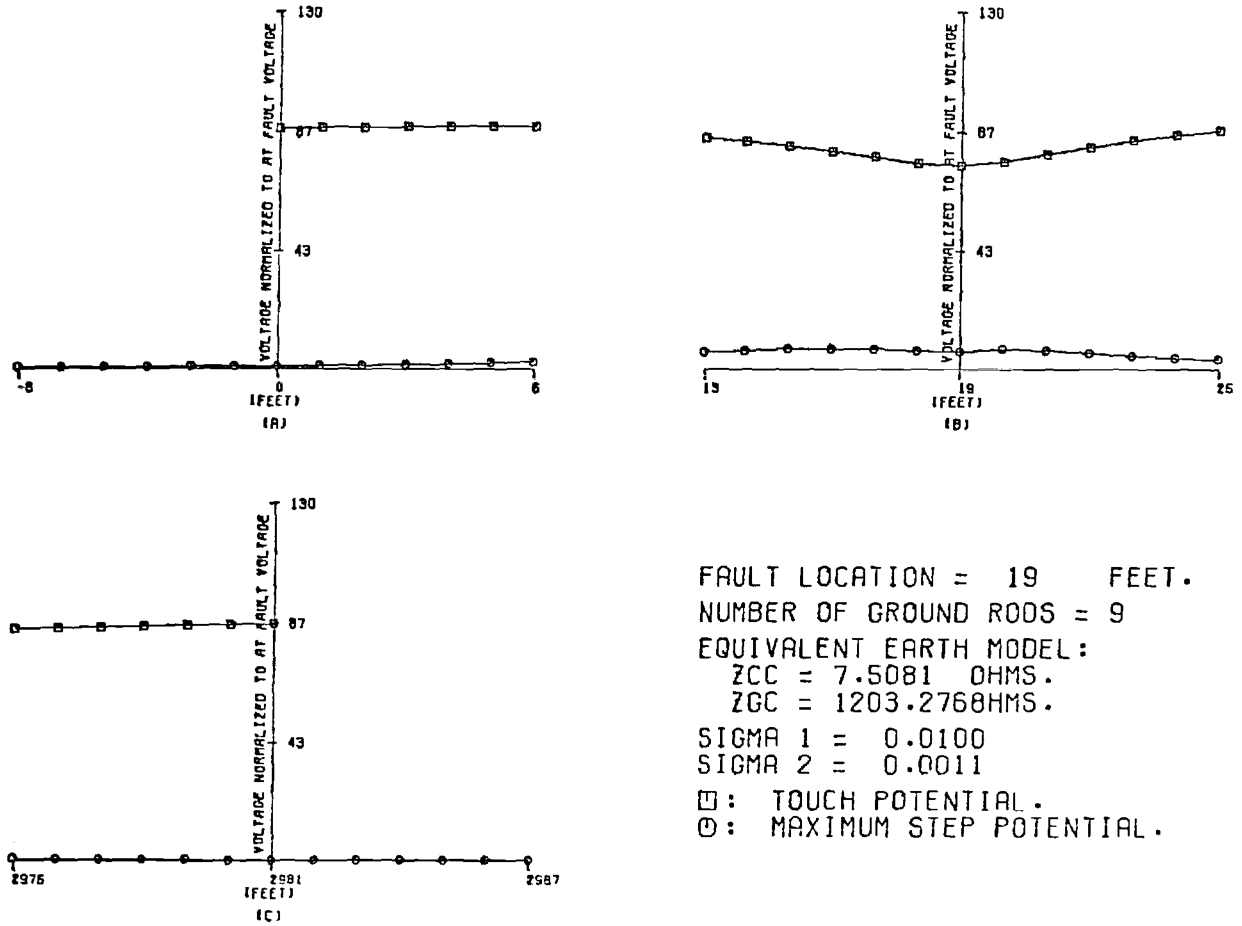
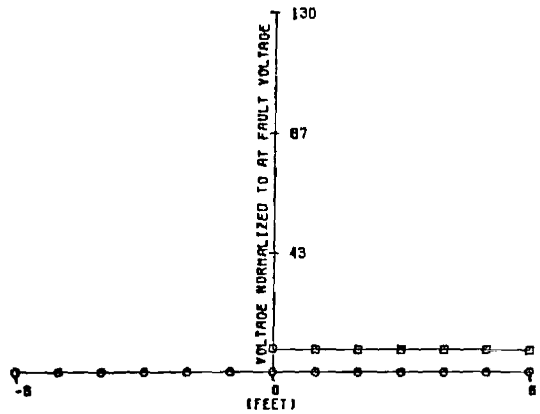
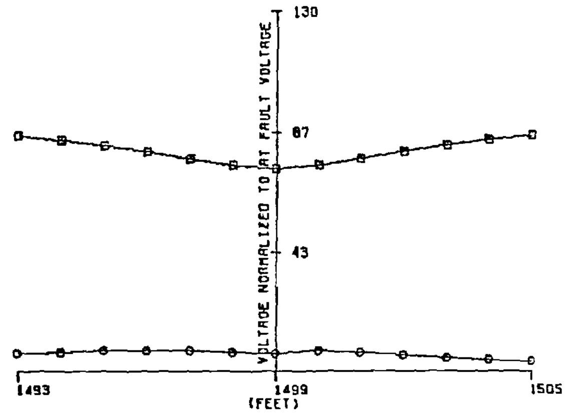
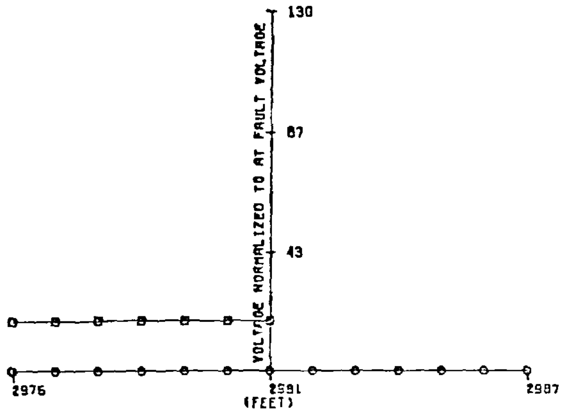


FIGURE A.6. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

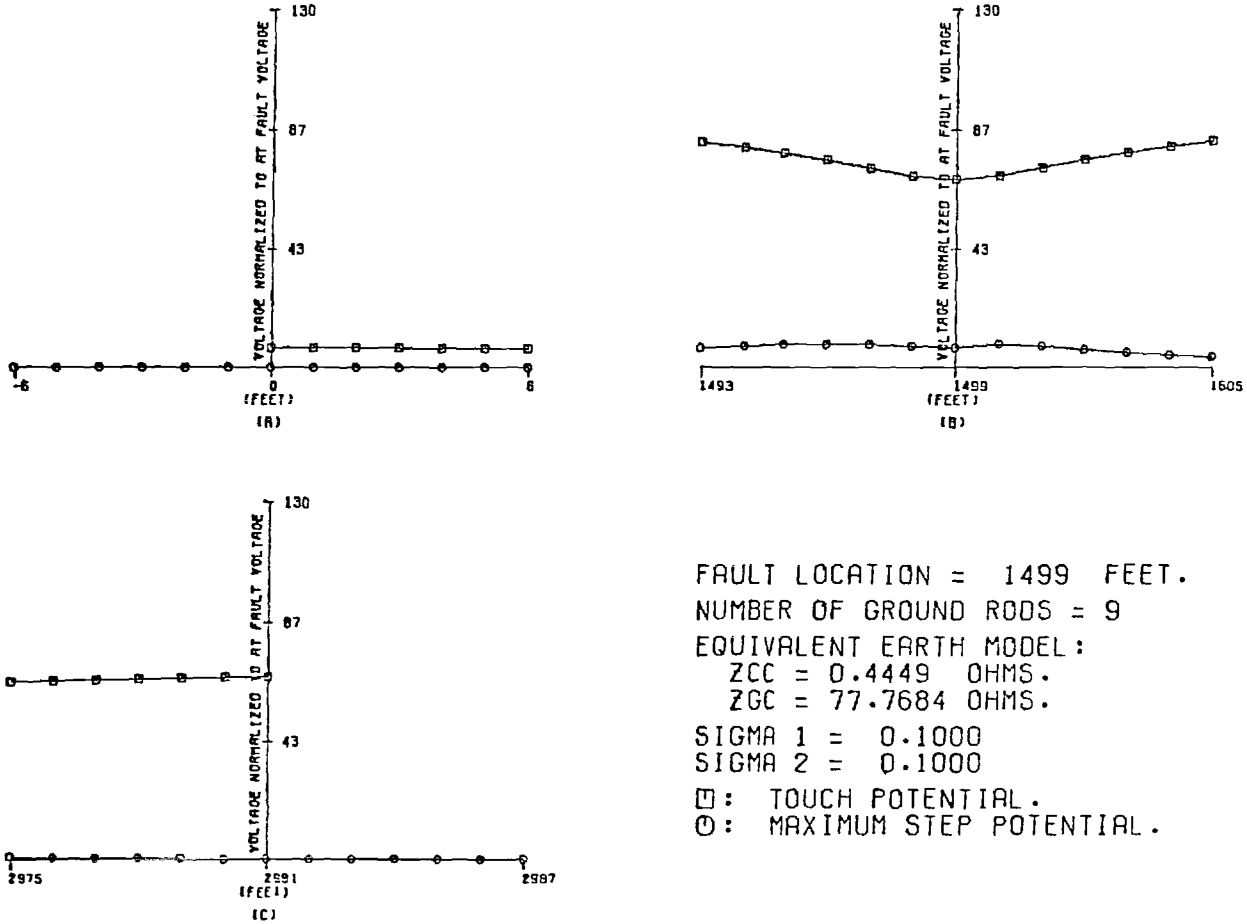






FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1363 OHMS.
ZGC = 19.7247 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.7. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.4449 OHMS.
ZGC = 77.7684 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.8. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

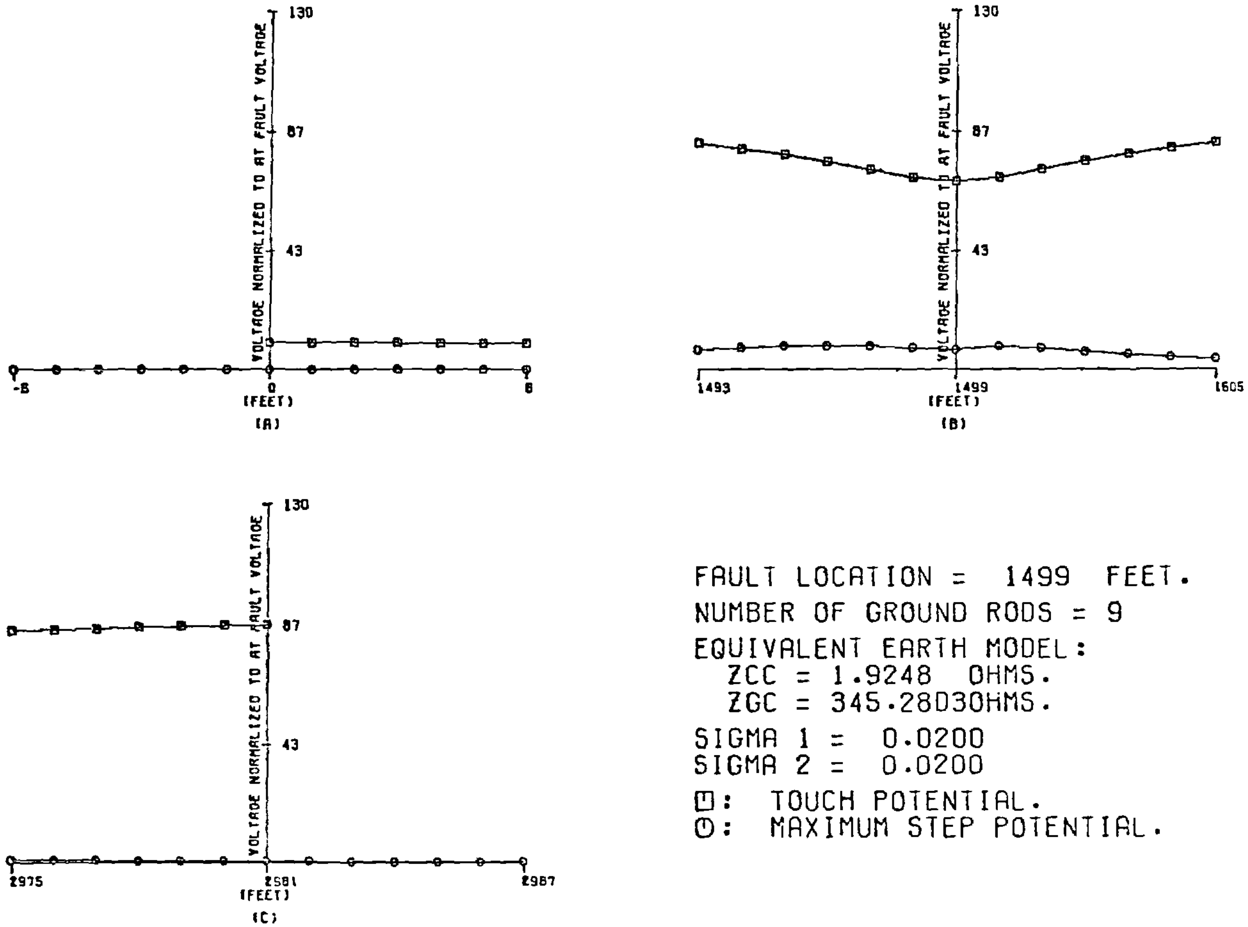


FIGURE A.9. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

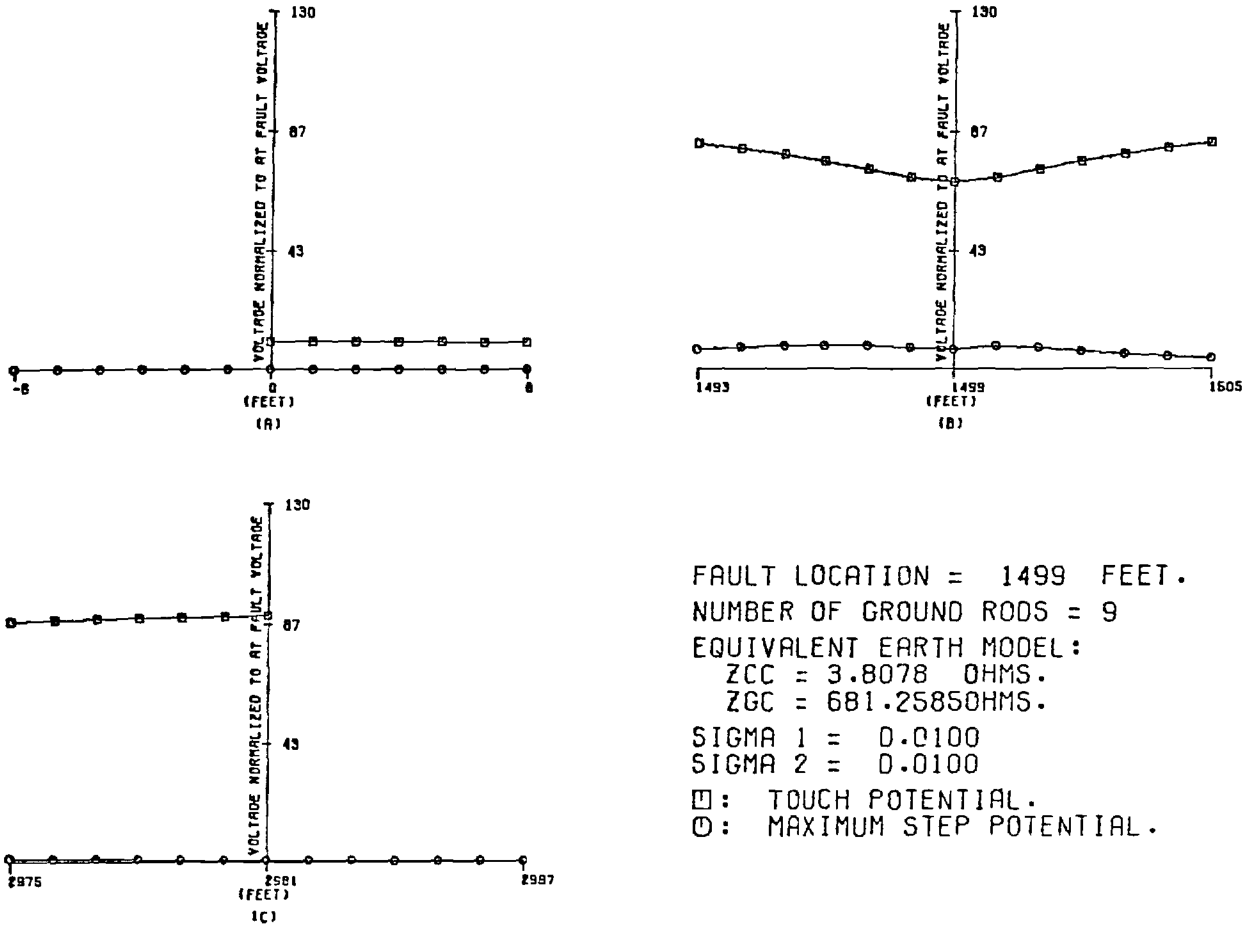


FIGURE A.10. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

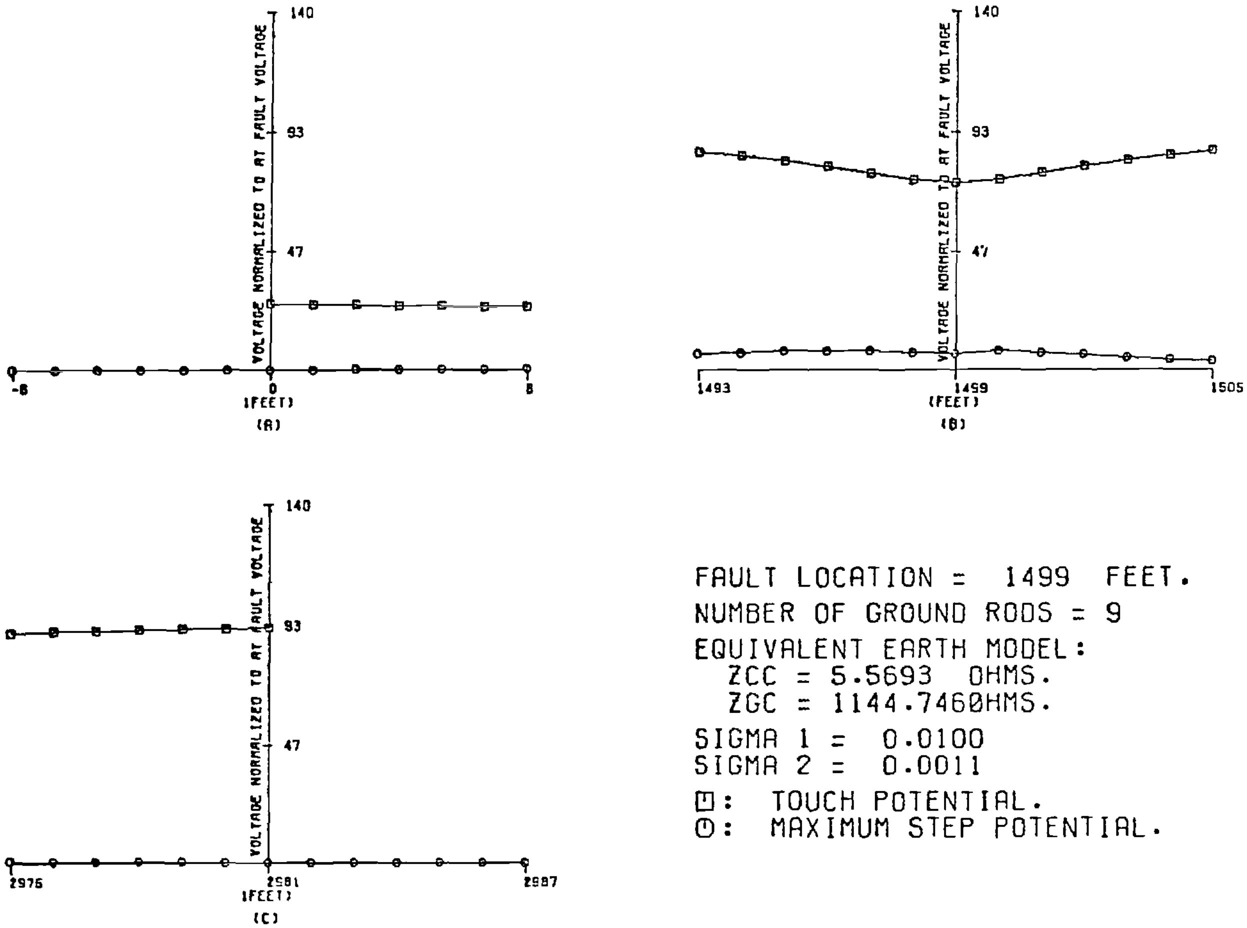


FIGURE A.11. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

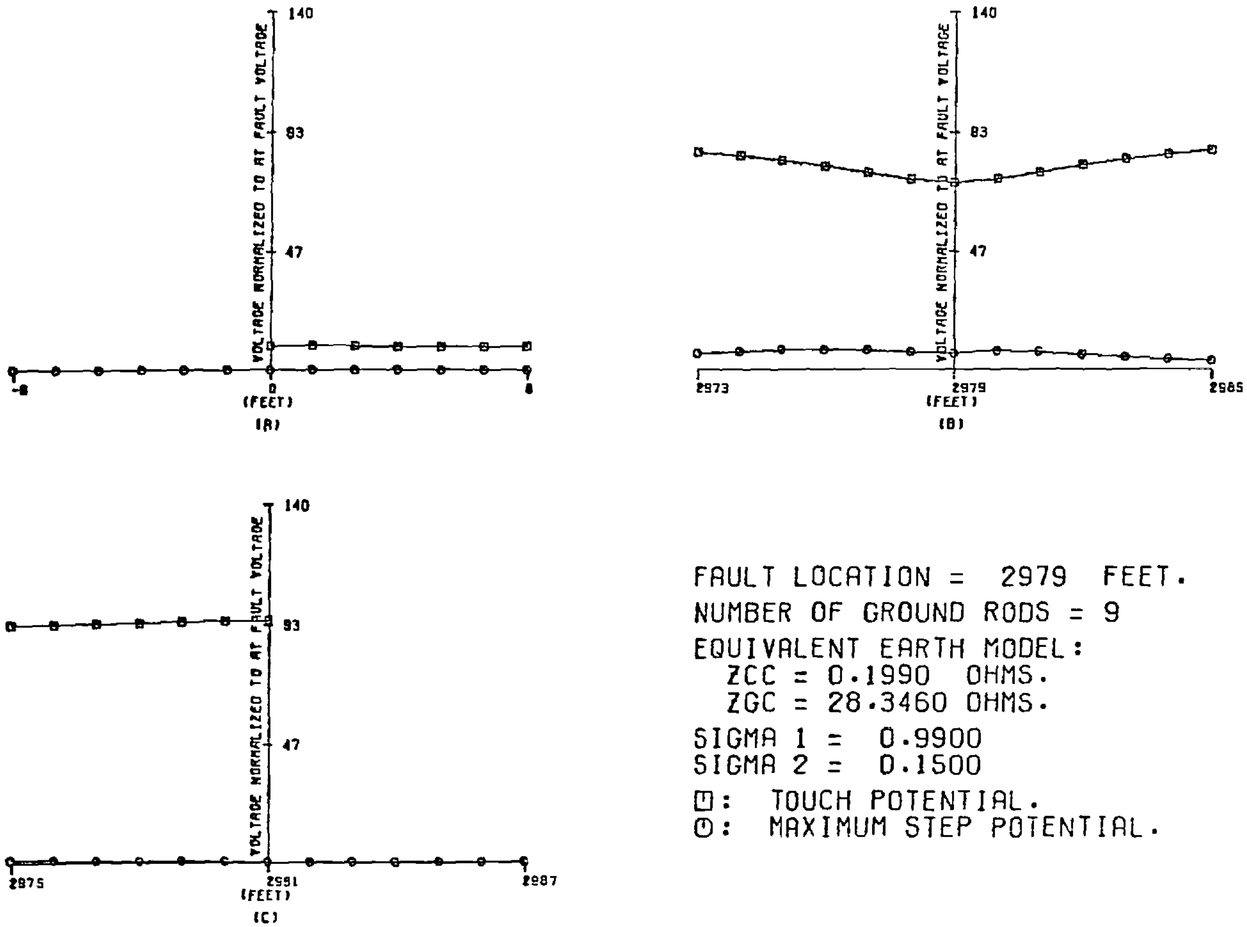


FIGURE A.12. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

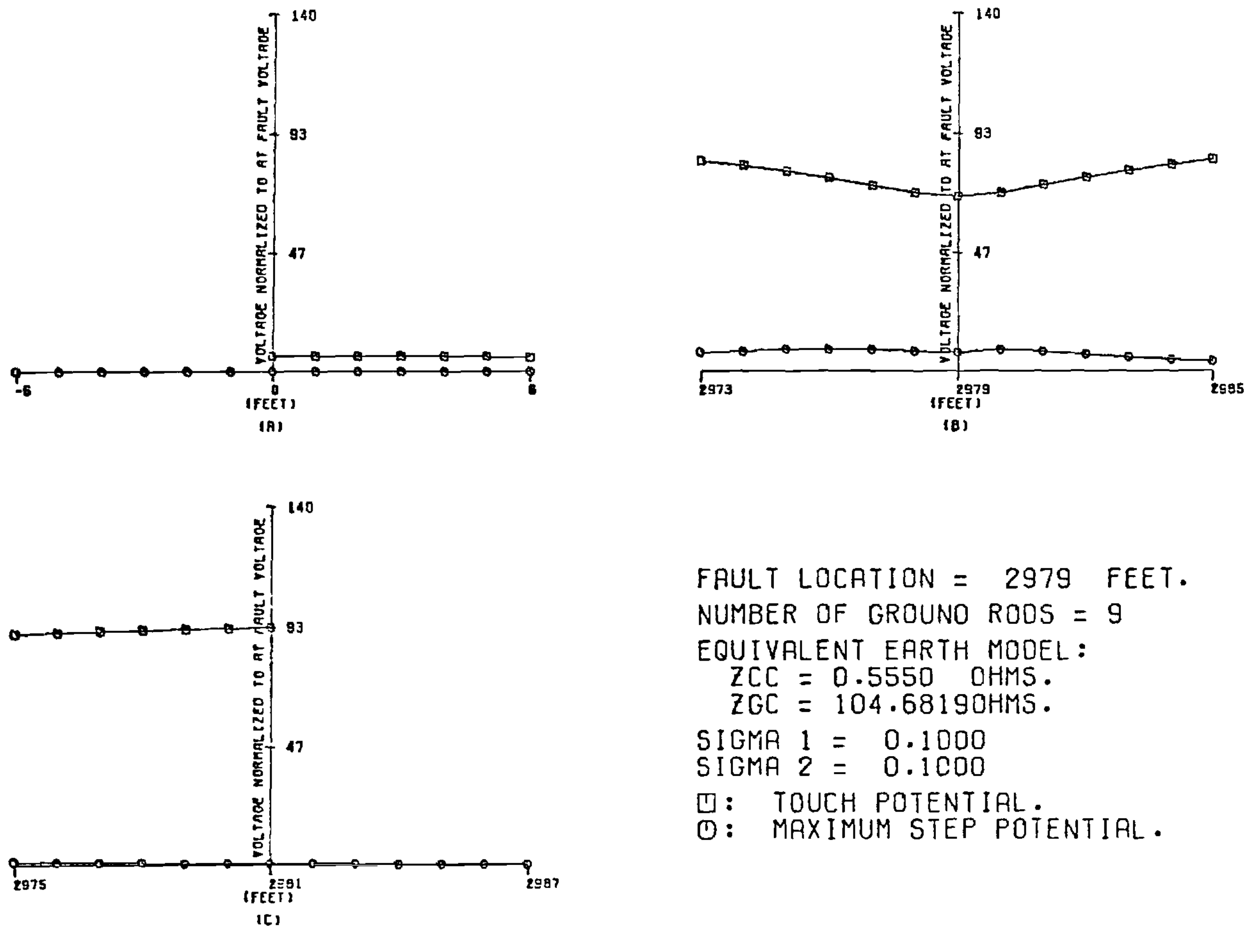


FIGURE A.13. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

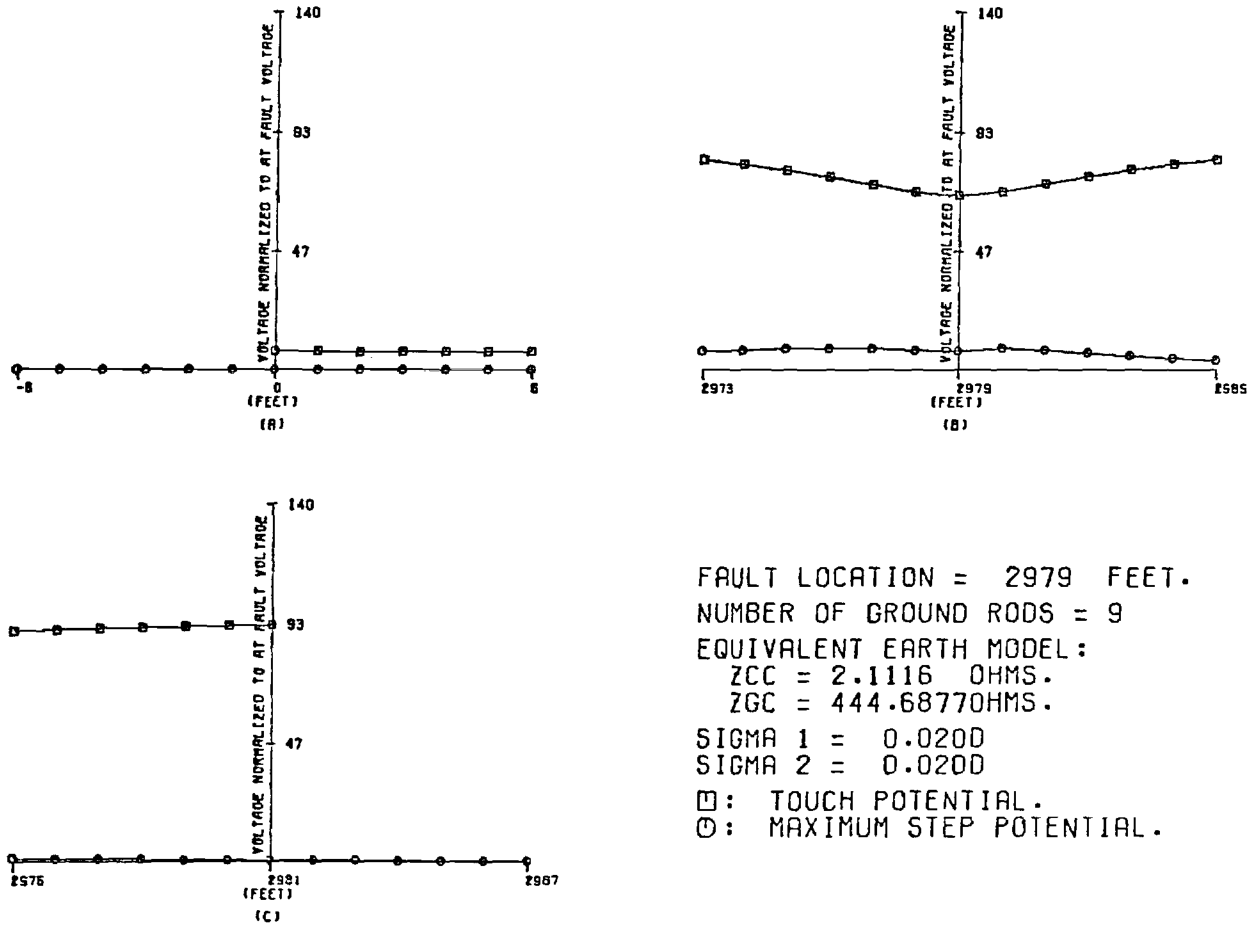
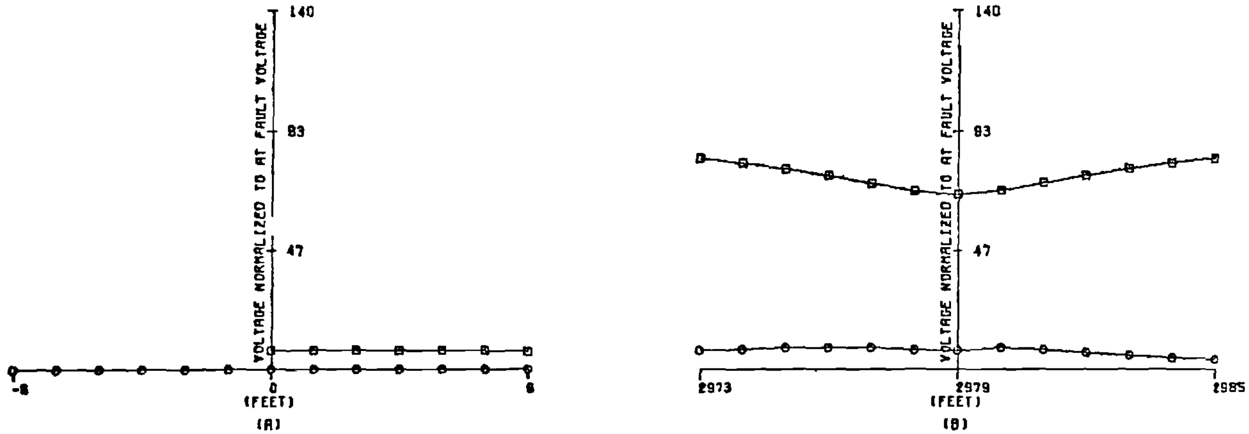
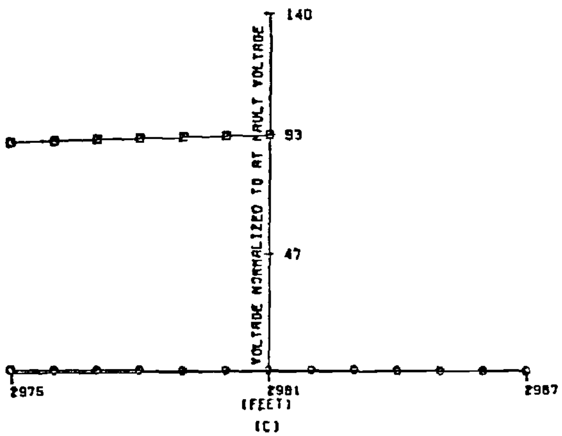


FIGURE A.14. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 4.1183 OHMS.
ZGC = 872.7690OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
☐: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE A.15. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

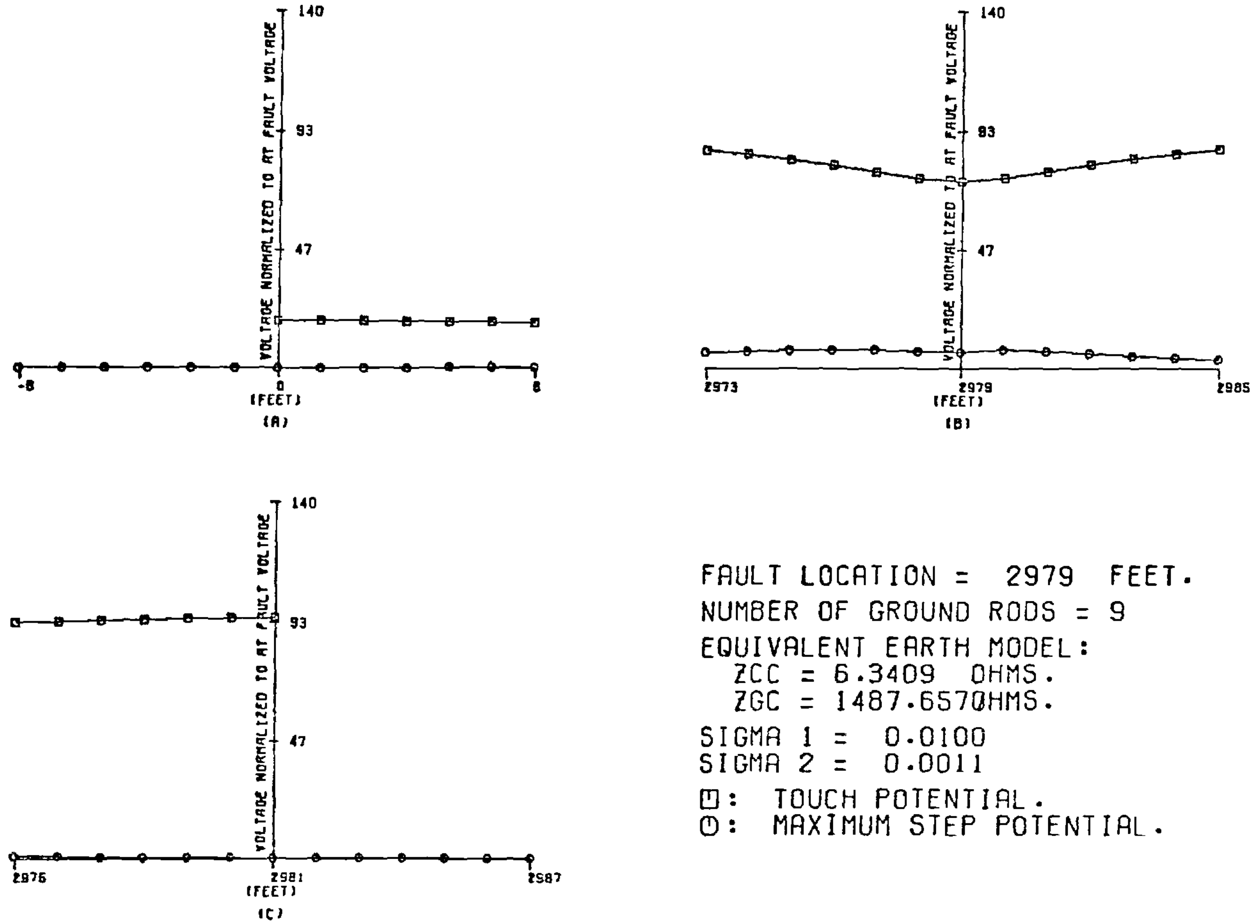


FIGURE A.16. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

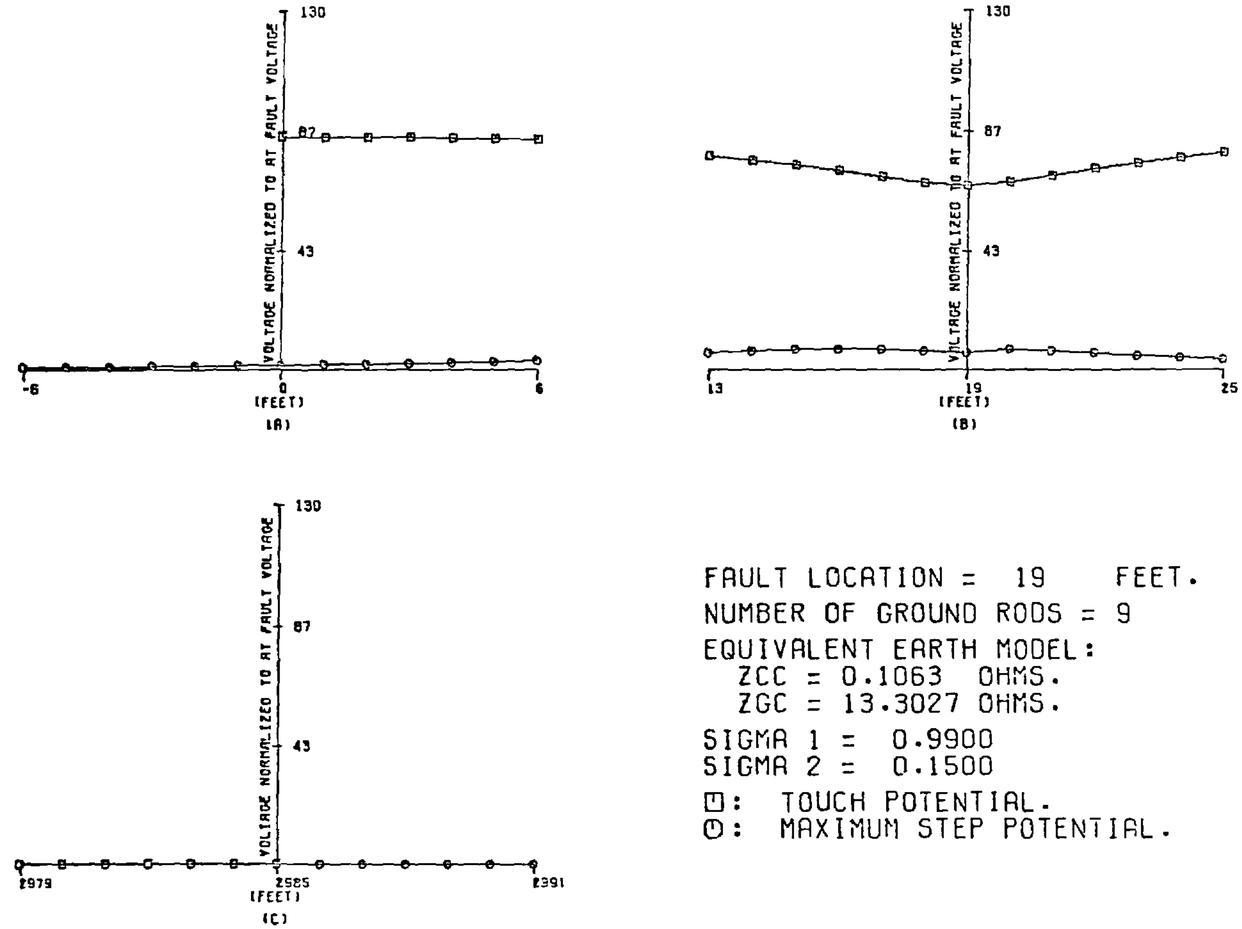
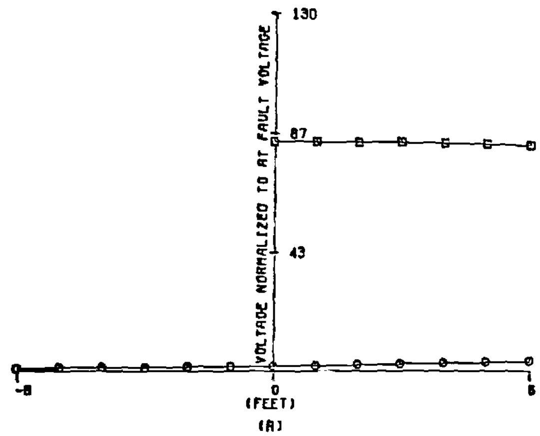
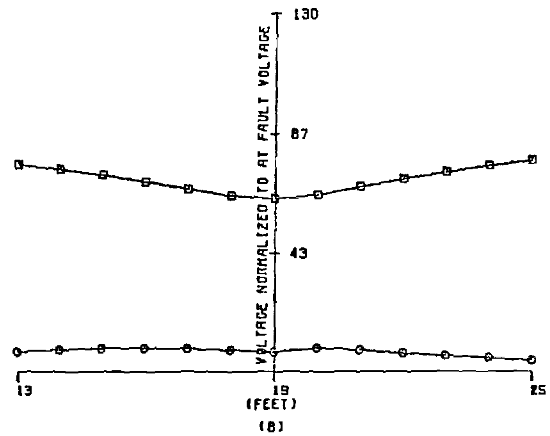
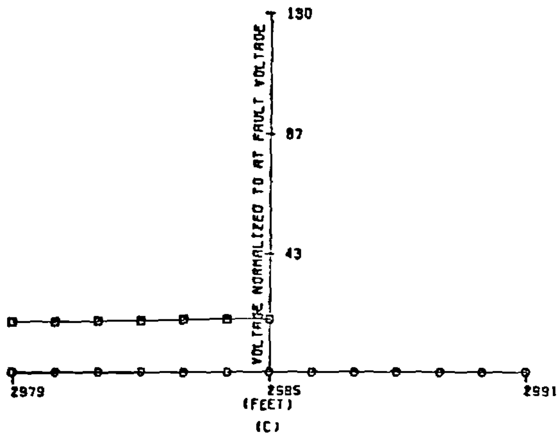


FIGURE A.17. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.3935 OHMS.
ZGC = 47.2330 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.18. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

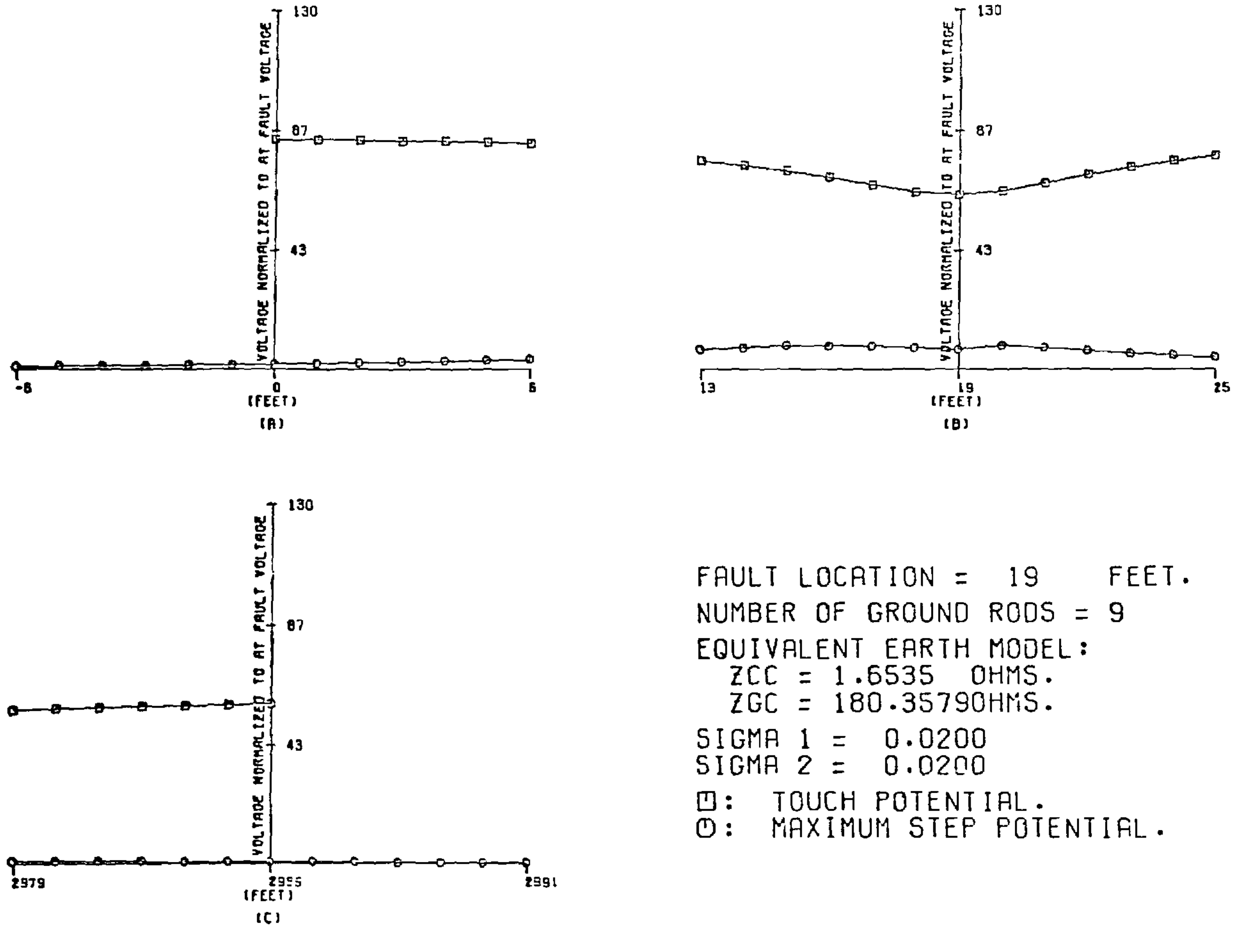
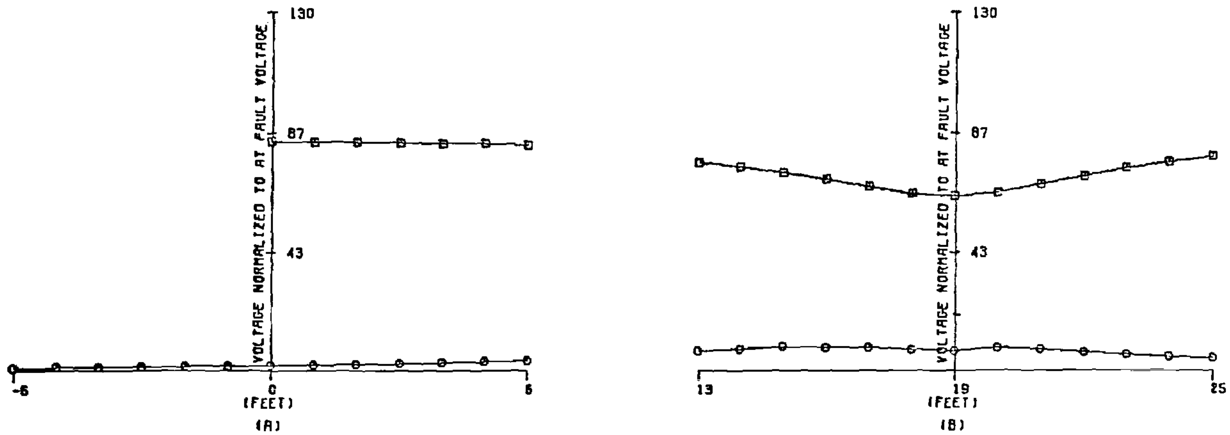
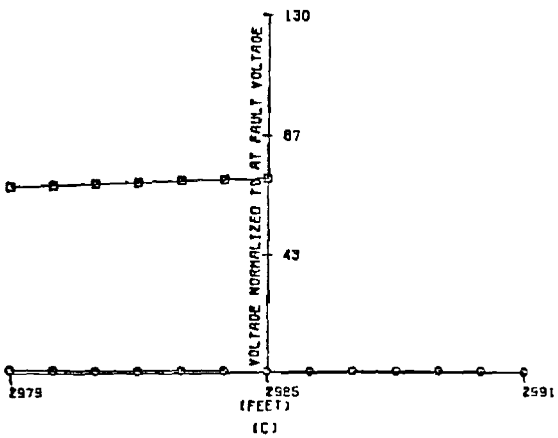


FIGURE A.19. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 3.1860 OHMS.
ZGC = 341.4272OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
◻: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.20. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

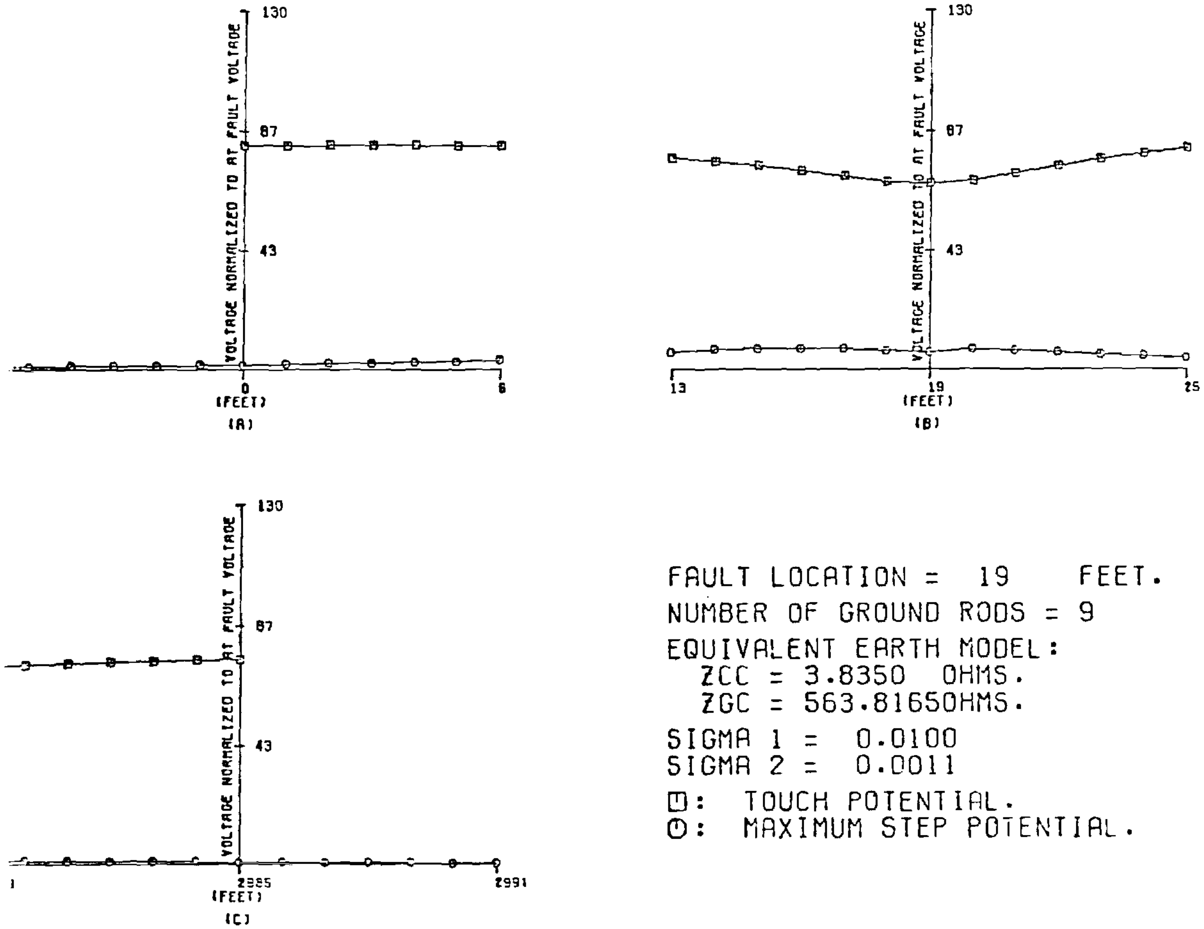


FIGURE A.21. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

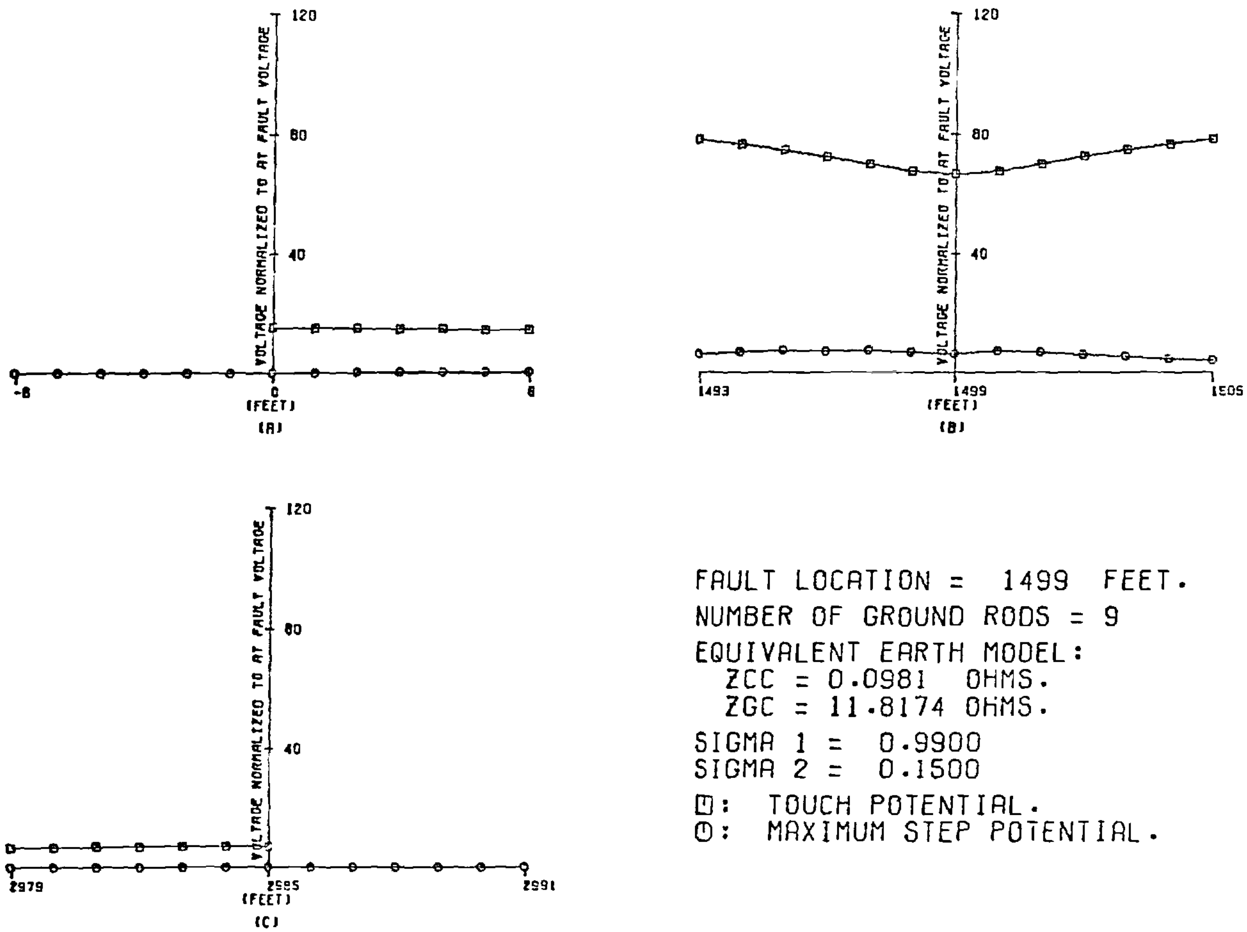


FIGURE A.22. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

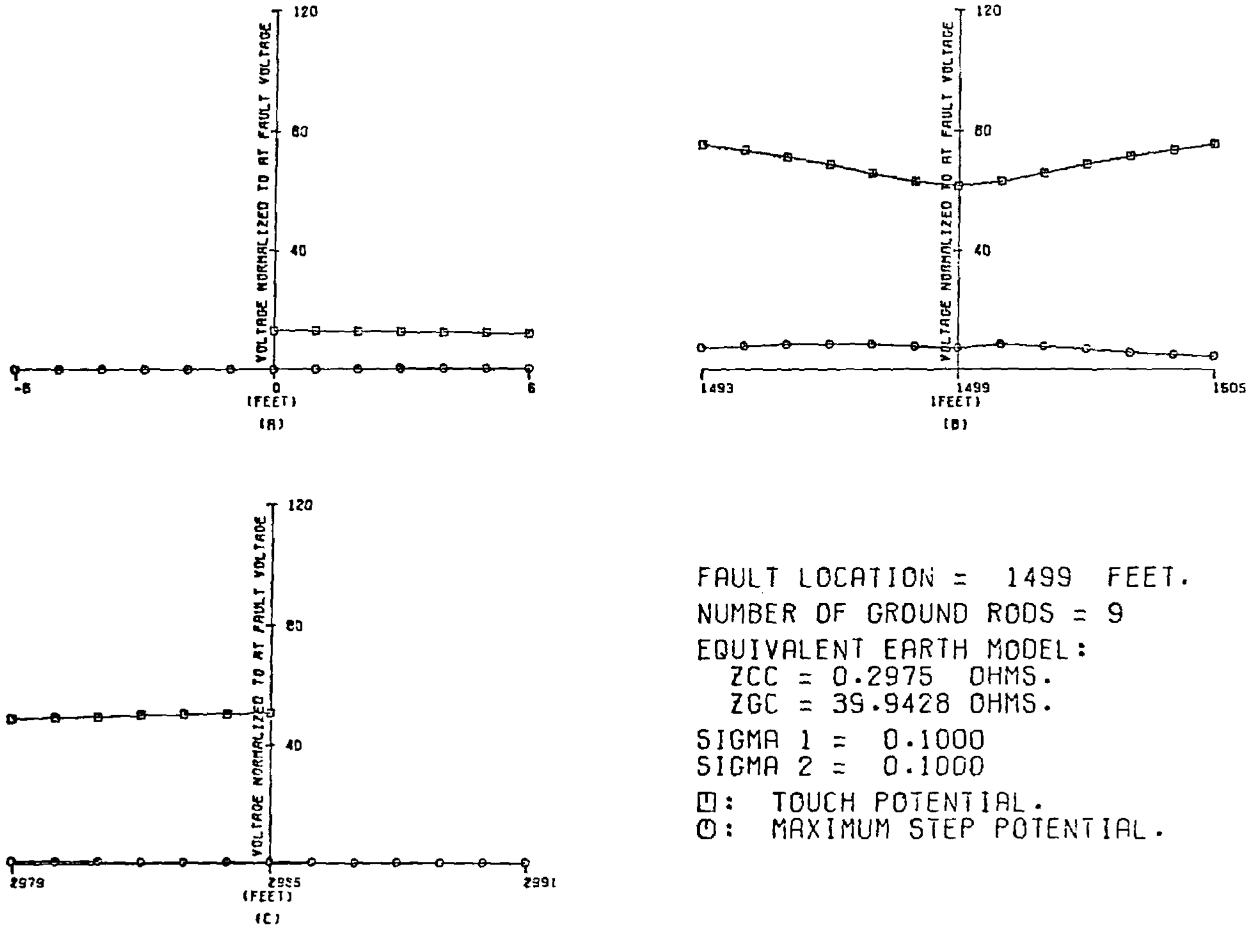


FIGURE A.23. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

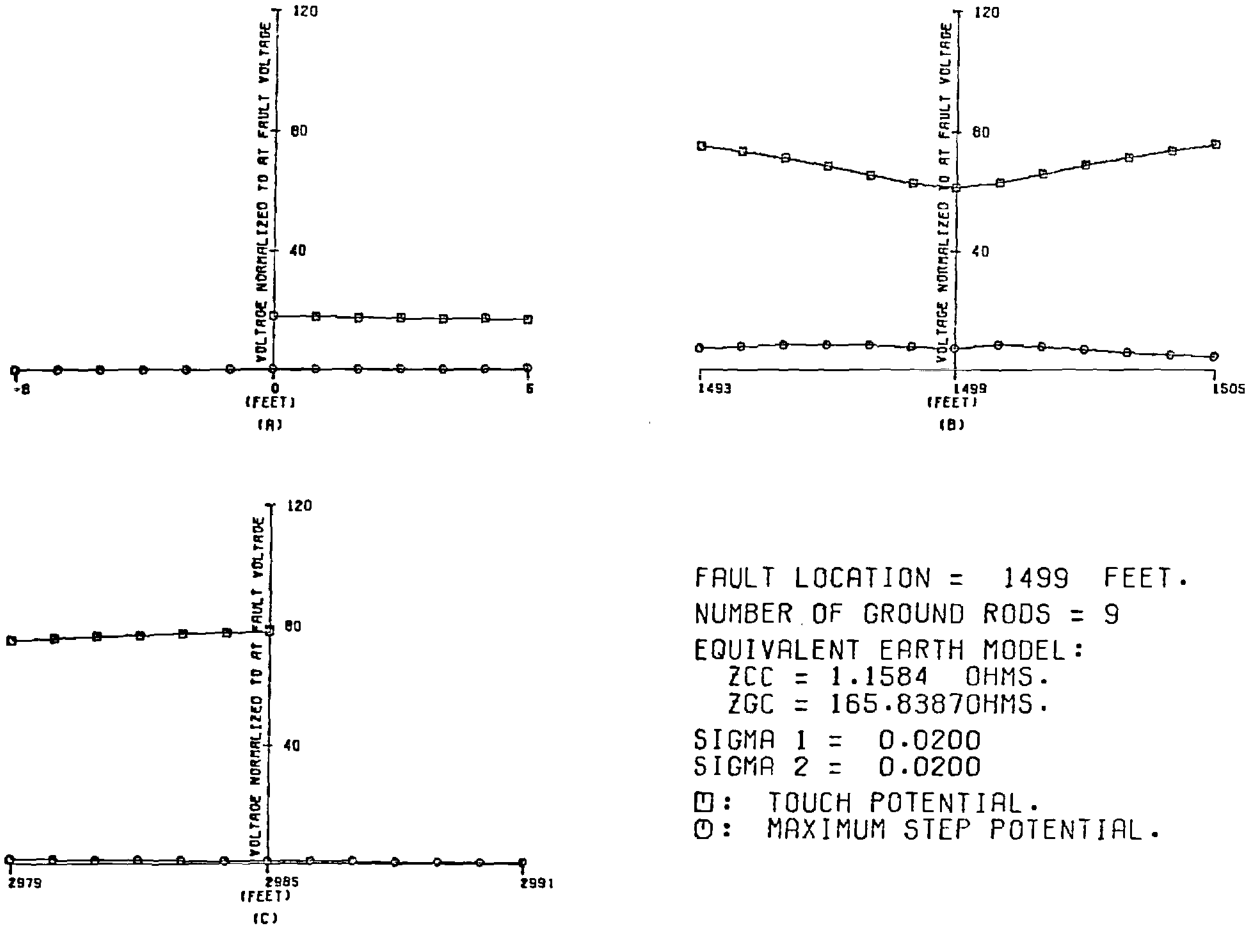
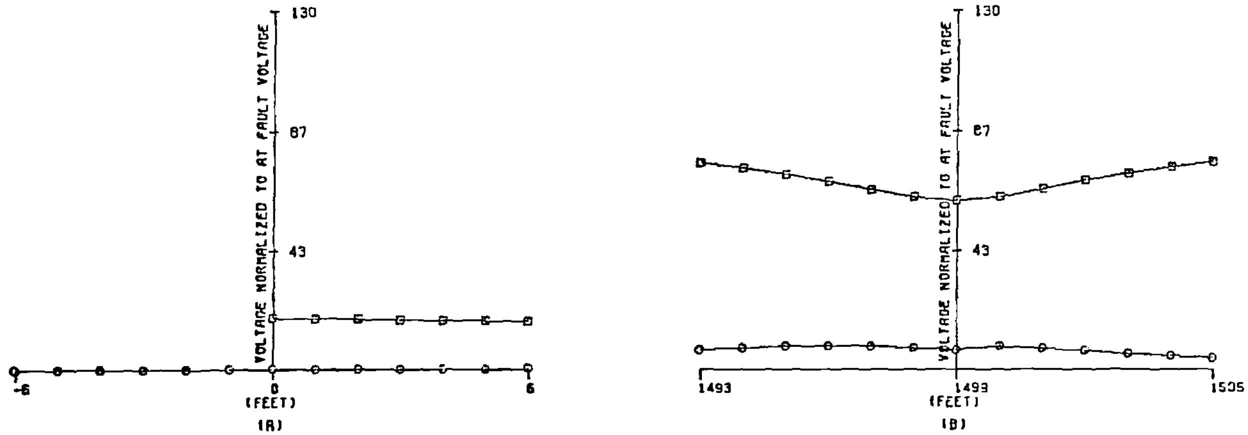
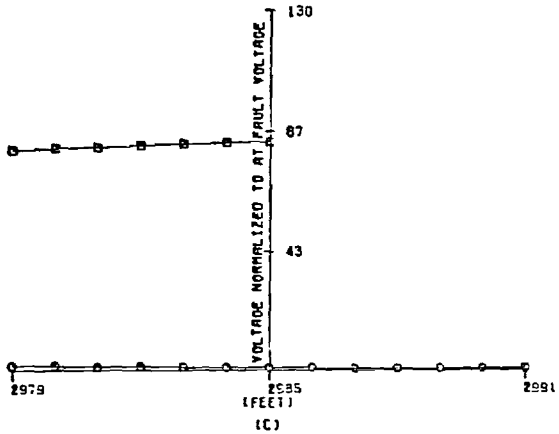


FIGURE A.24. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 2.2671 OHMS.
ZGC = 324.5094OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.25. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

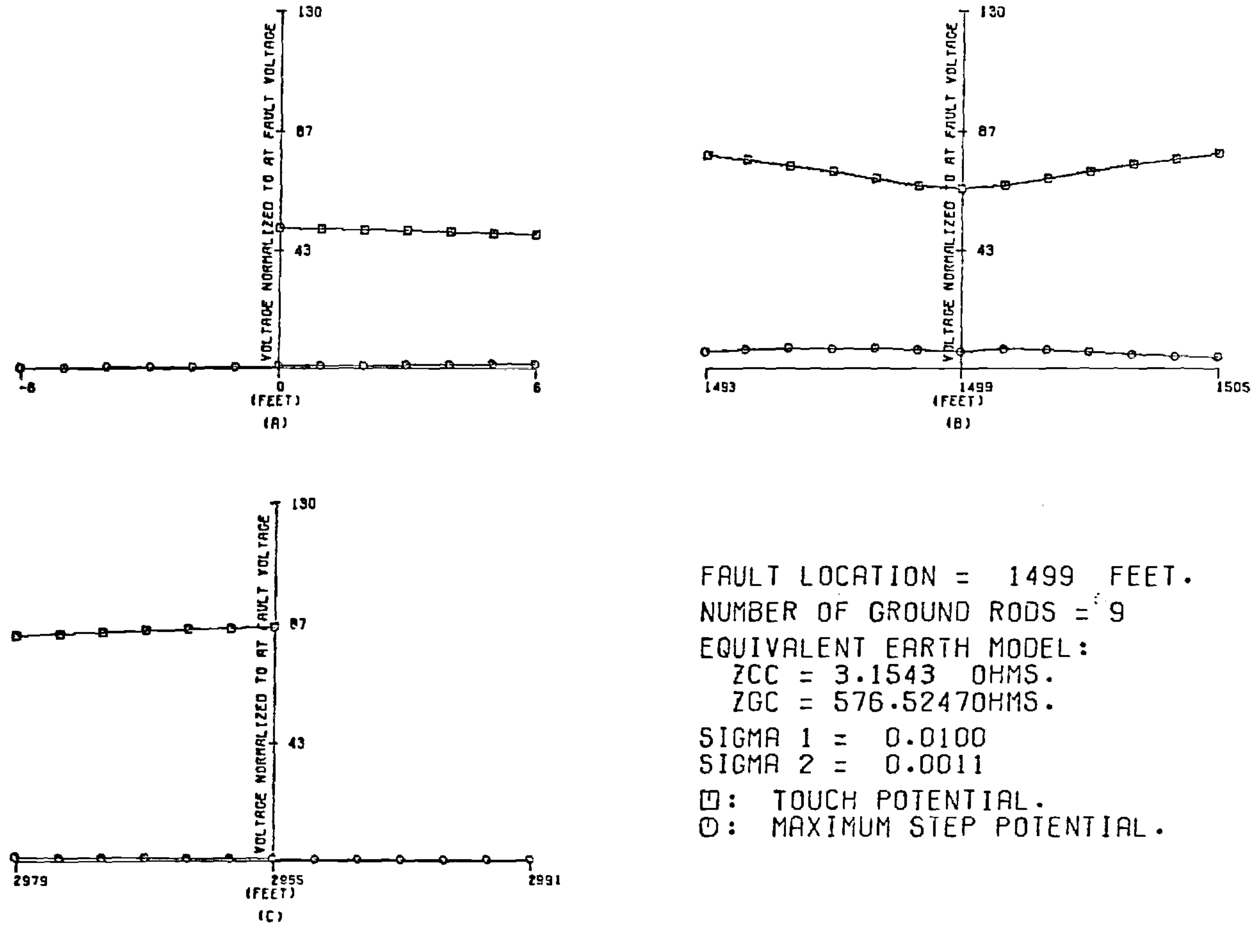


FIGURE A.26. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

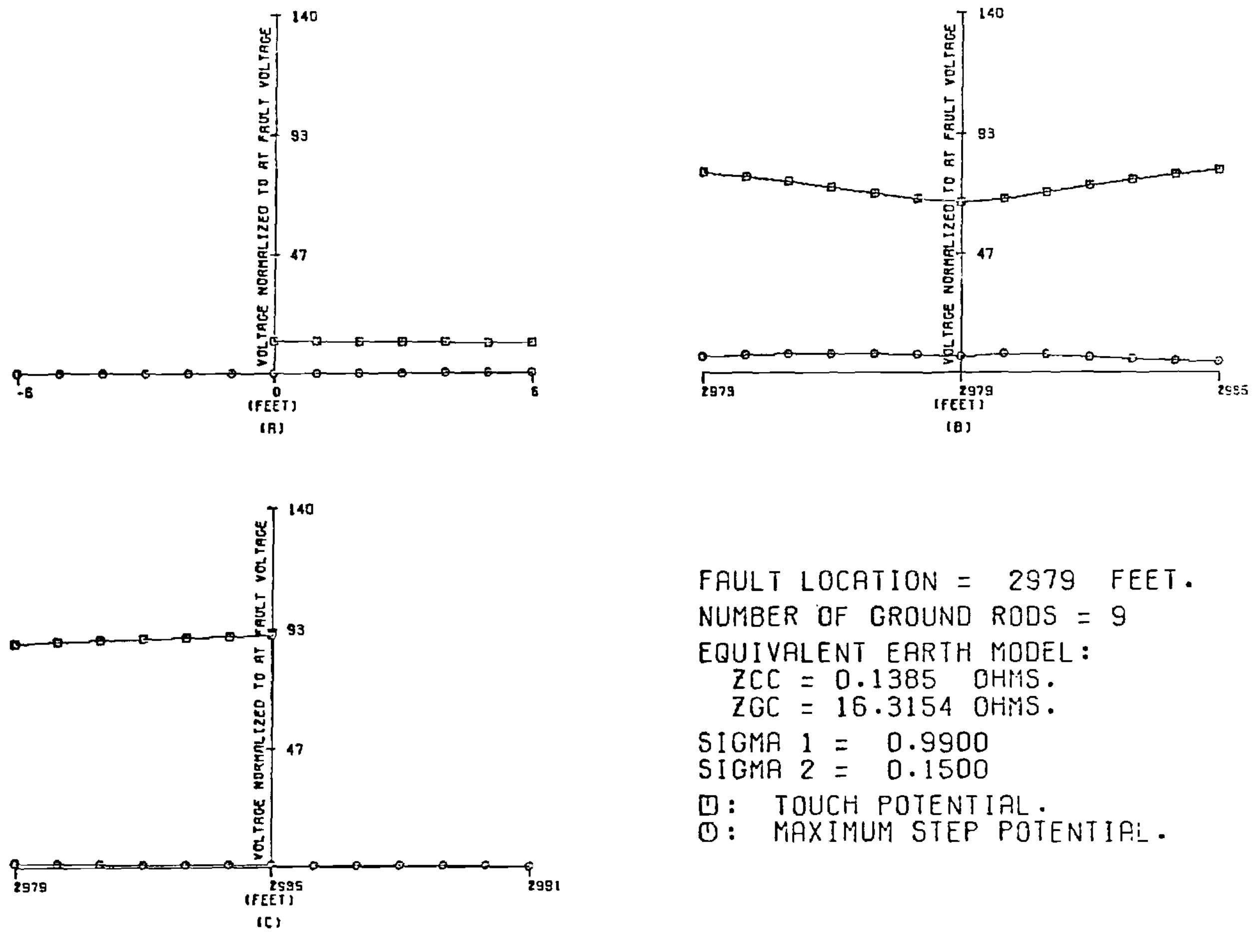


FIGURE A.27. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

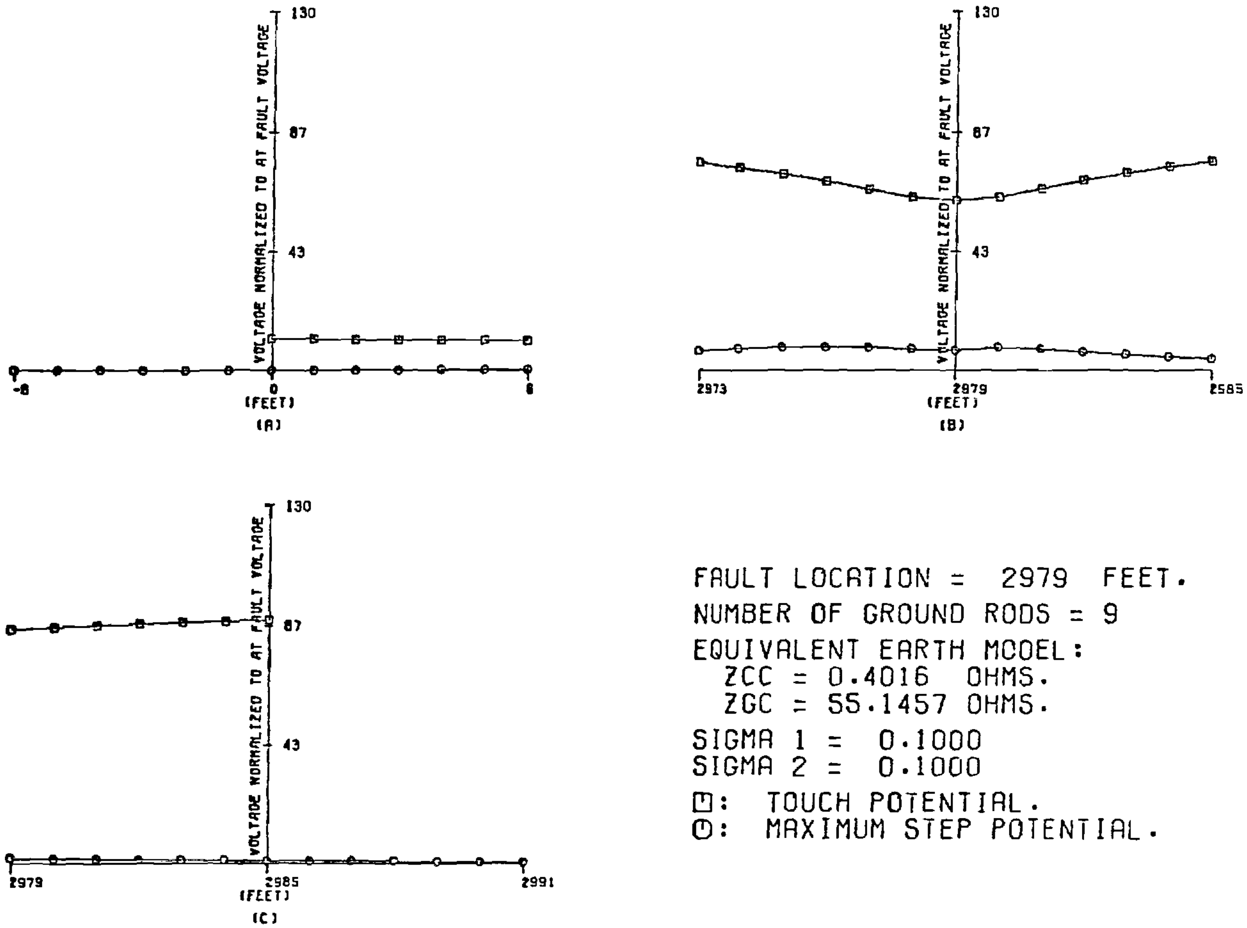
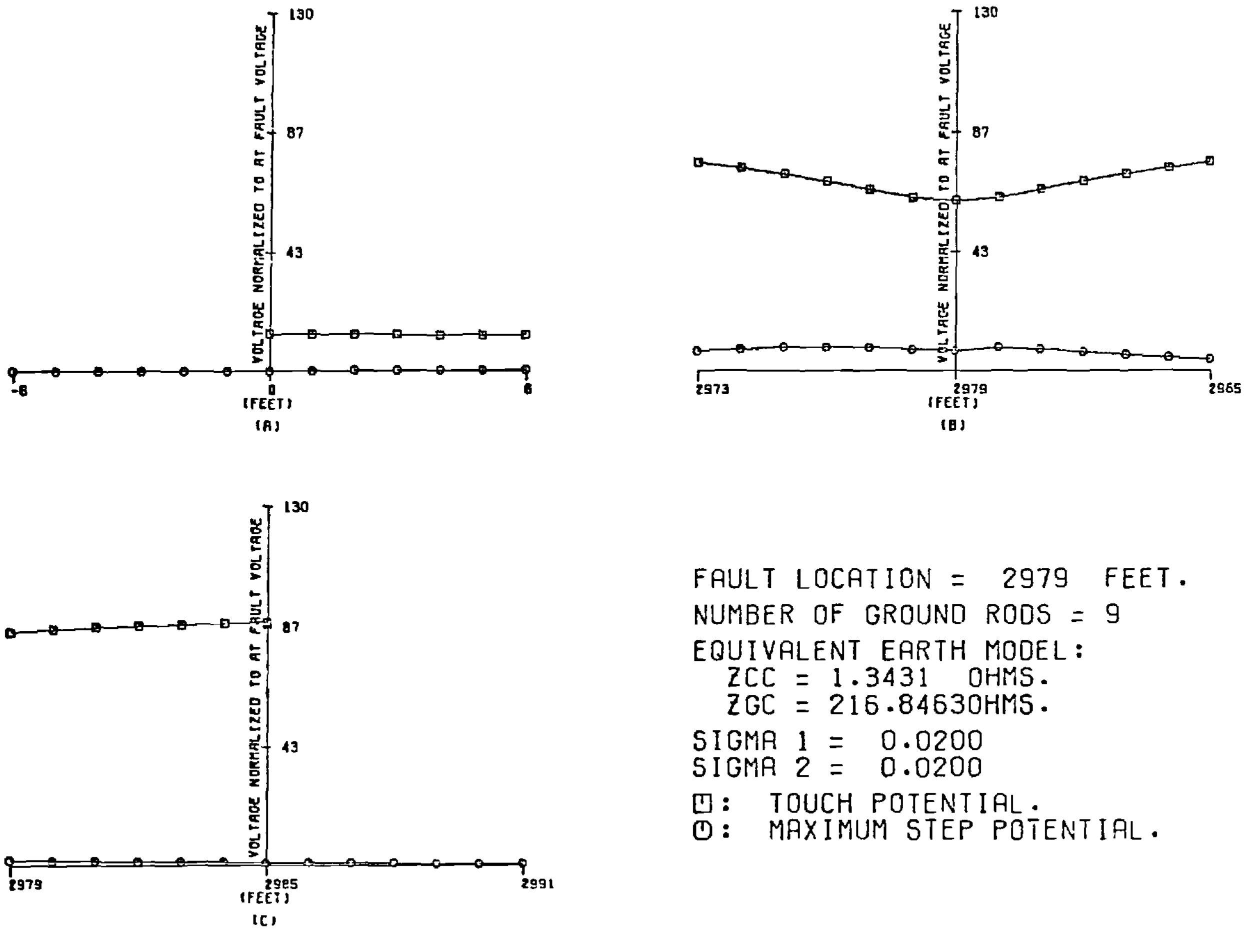


FIGURE A.28. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.

NUMBER OF GROUND RODS = 9

EQUIVALENT EARTH MODEL:
ZCC = 1.3431 OHMS.
ZGC = 216.84630HMS.

SIGMA 1 = 0.0200
SIGMA 2 = 0.0200

□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.29. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

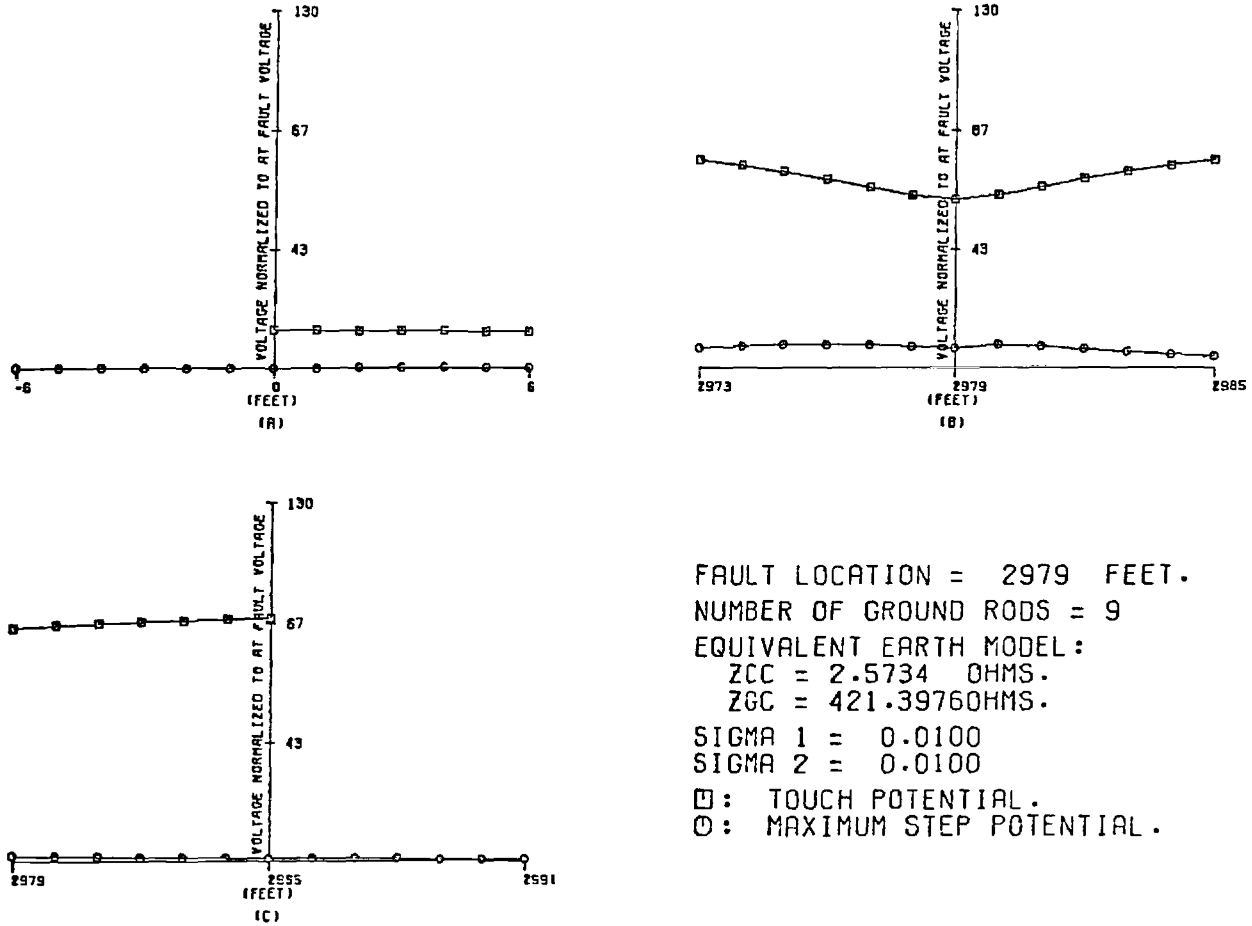


FIGURE A.30. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

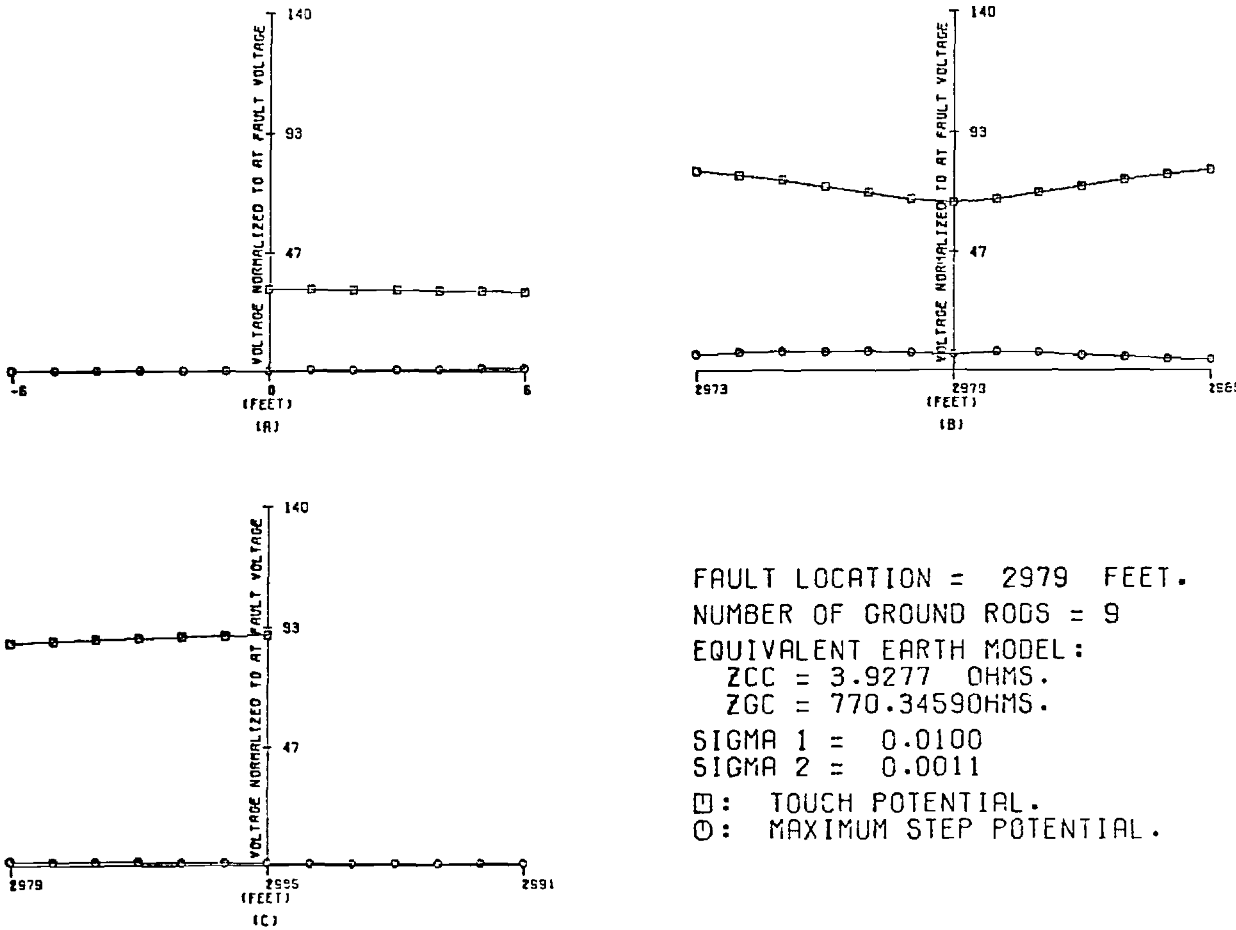
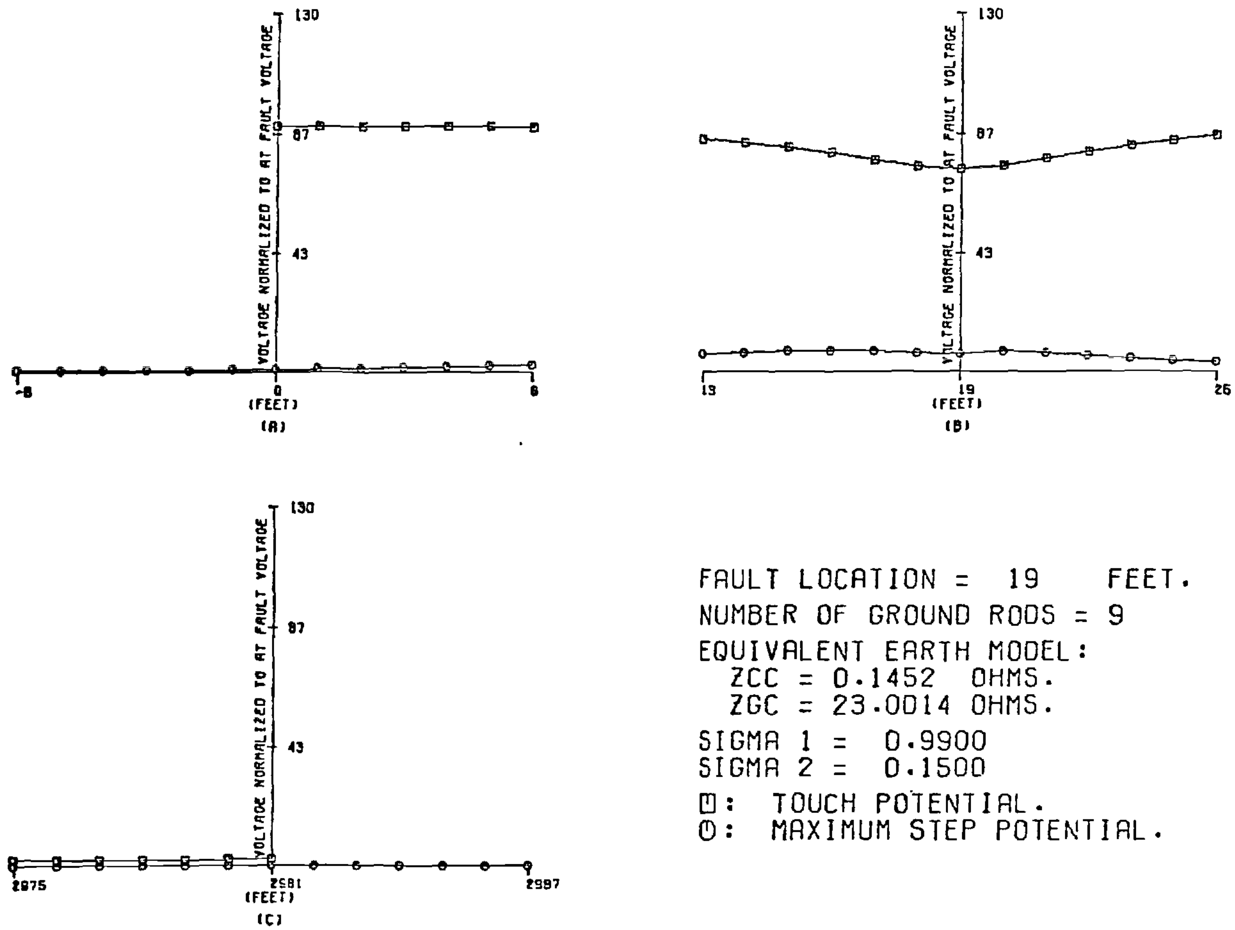
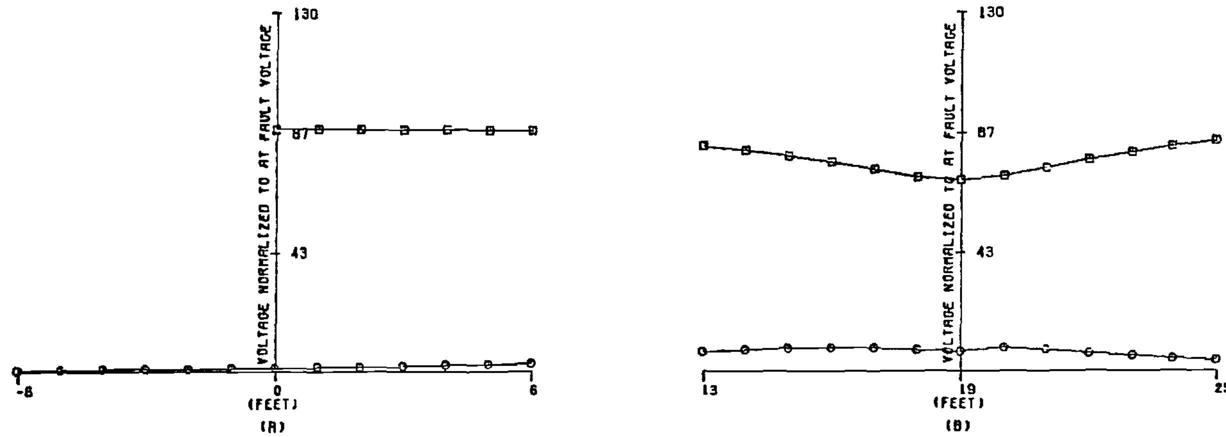


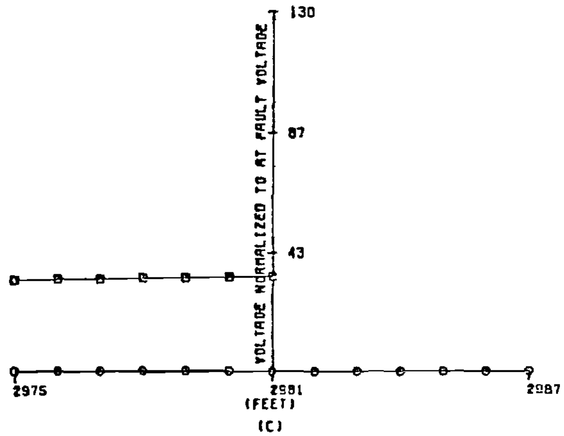
FIGURE A.31. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1452 OHMS.
ZGC = 23.0014 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.32. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.6163 OHMS.
ZGC = 91.2254 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.33. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

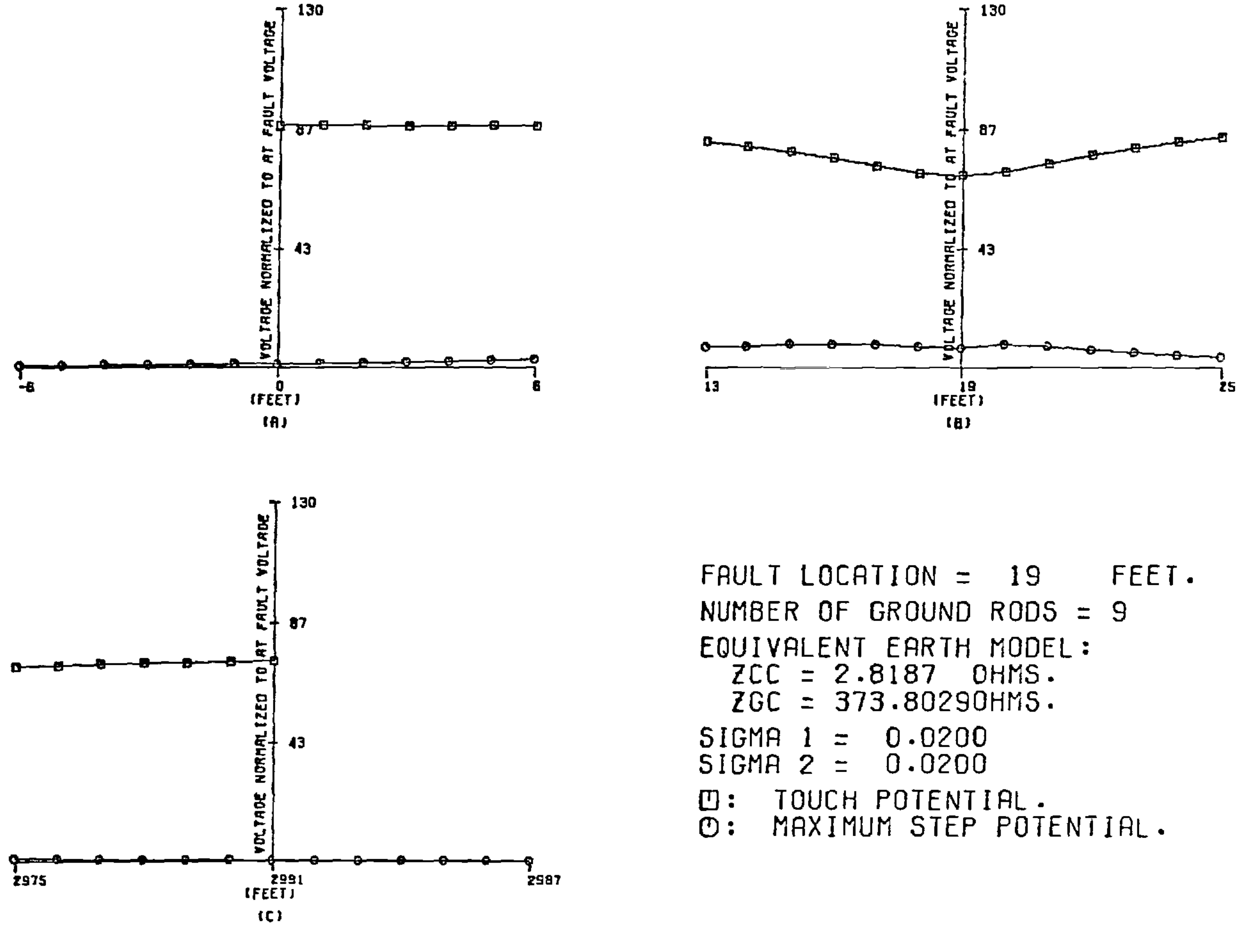


FIGURE A.34. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

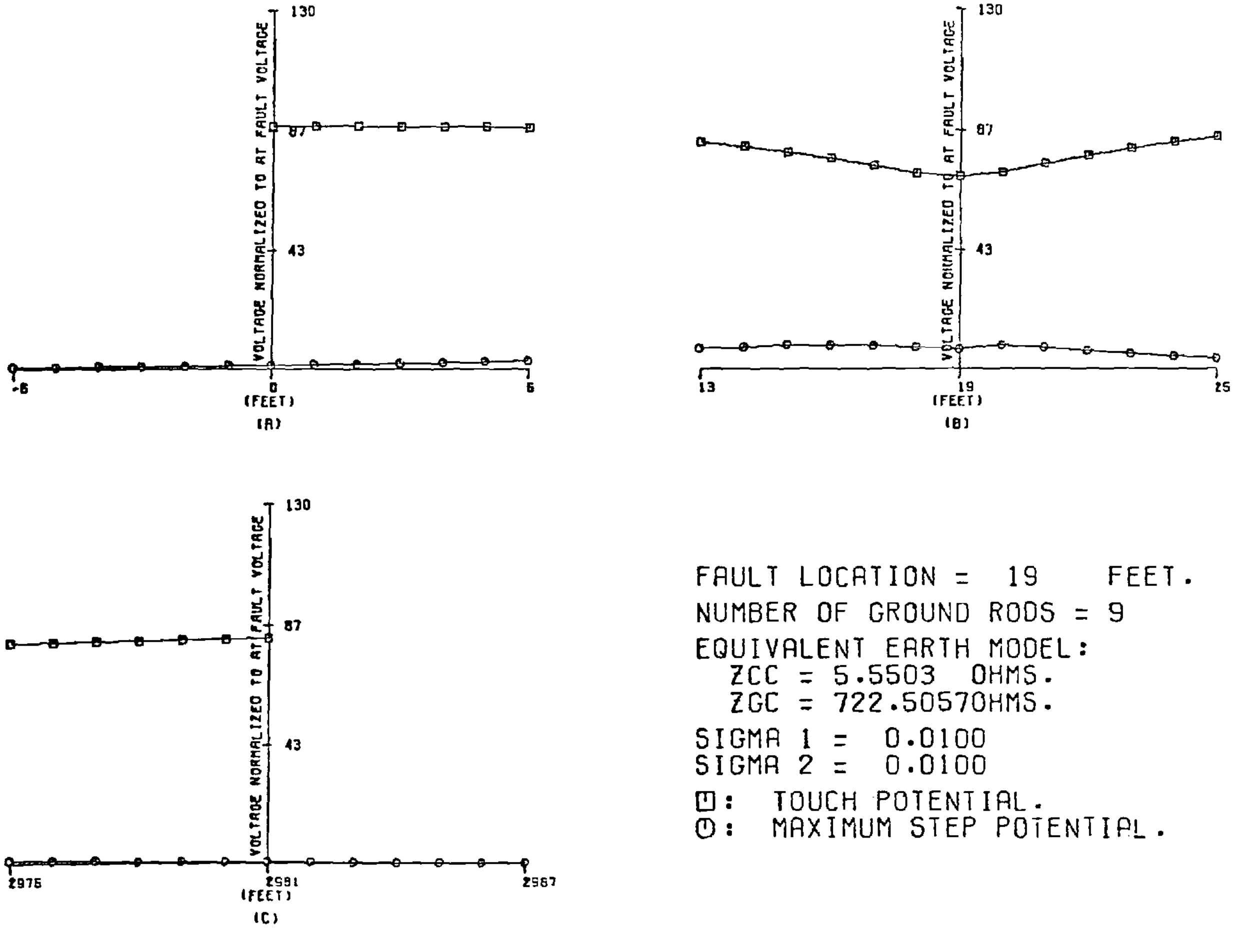


FIGURE A.35. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

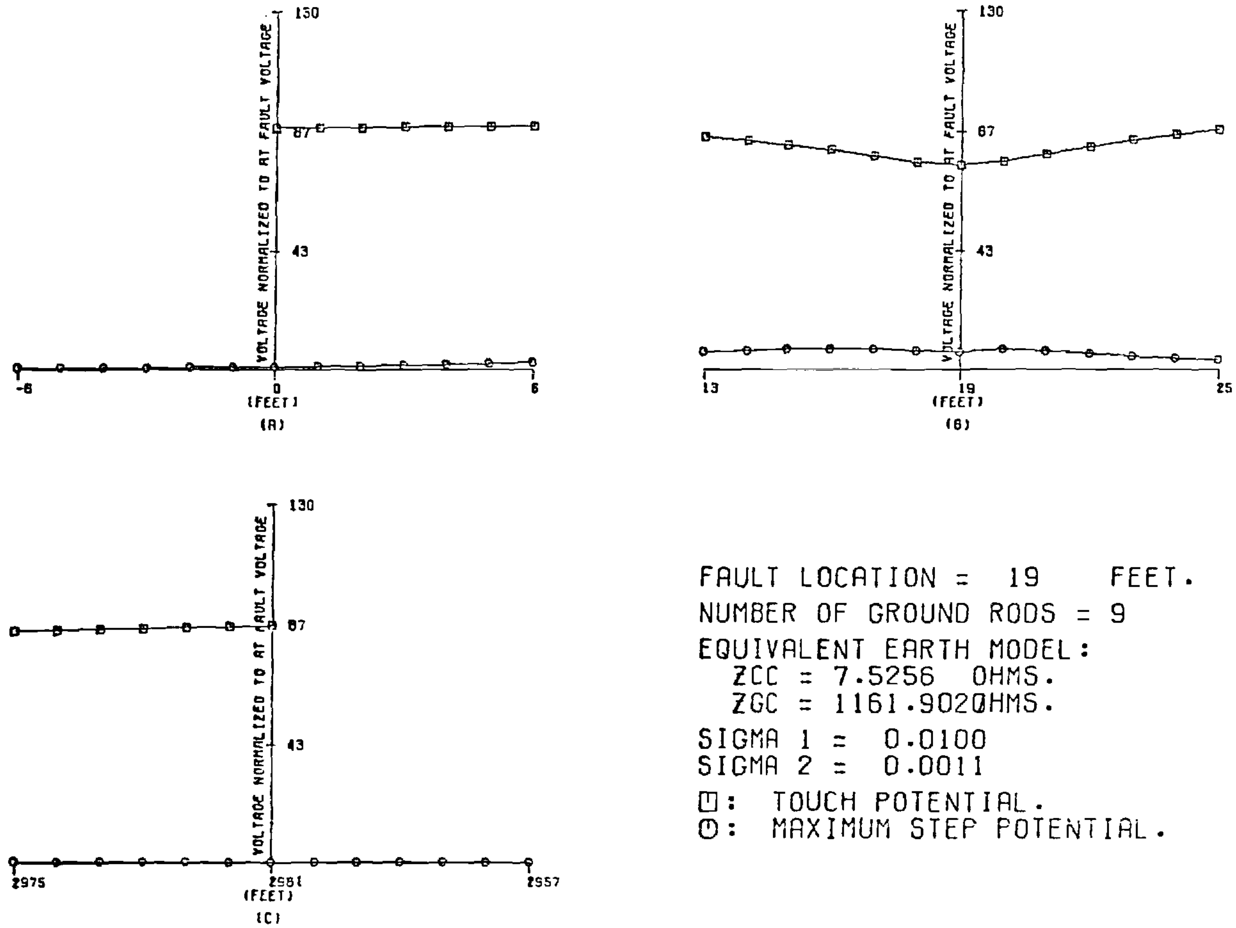


FIGURE A.36. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

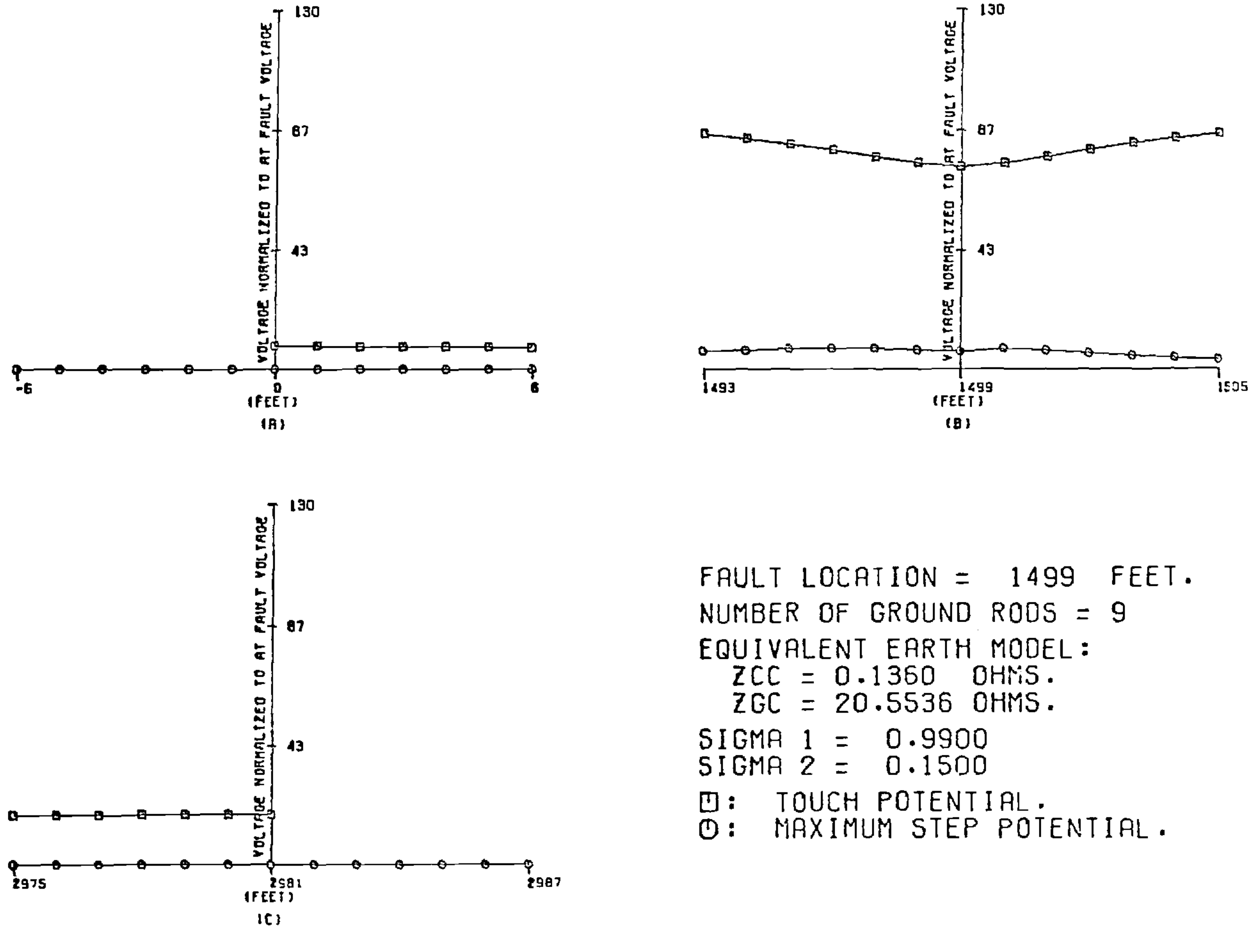


FIGURE A.37. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

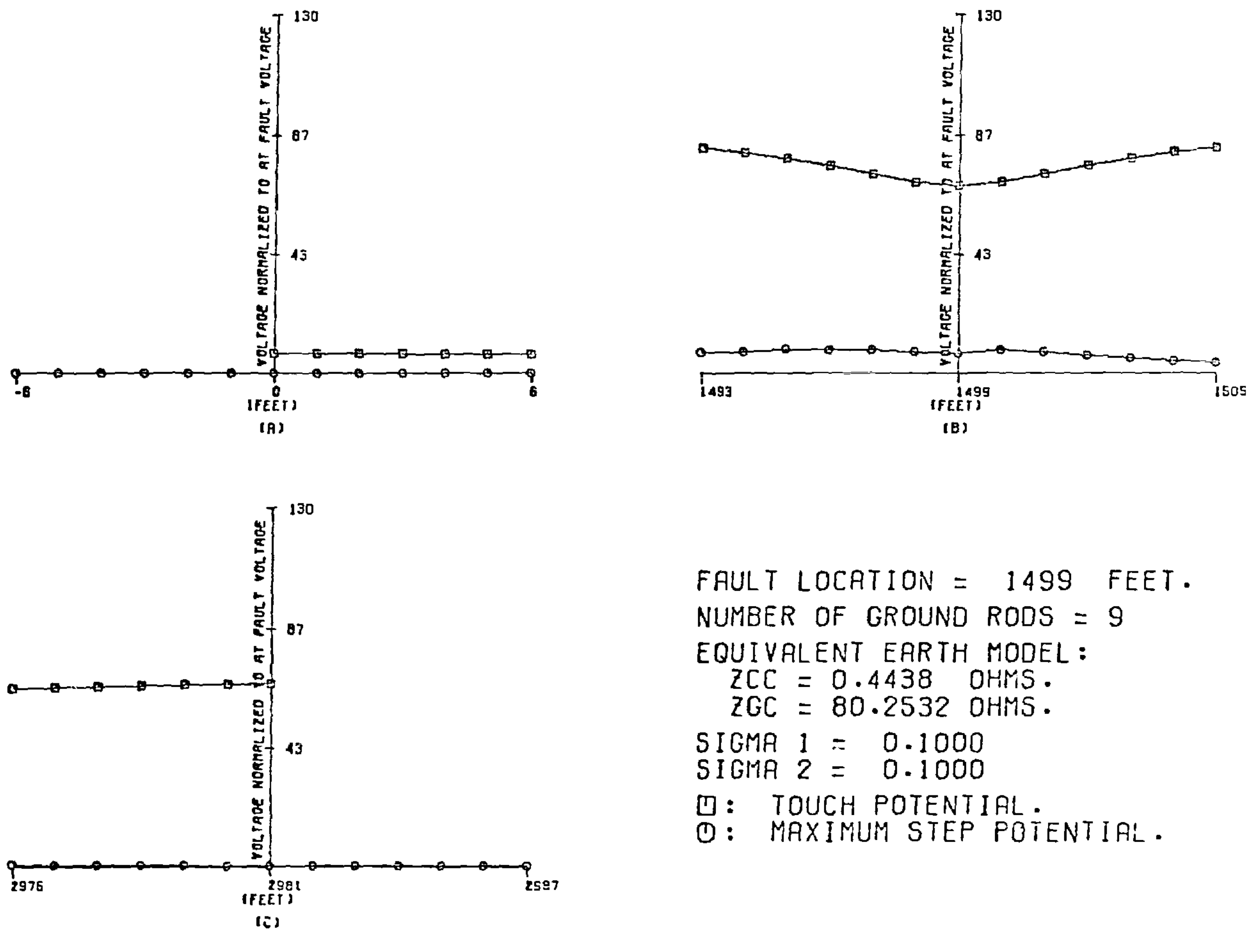


FIGURE A.38. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

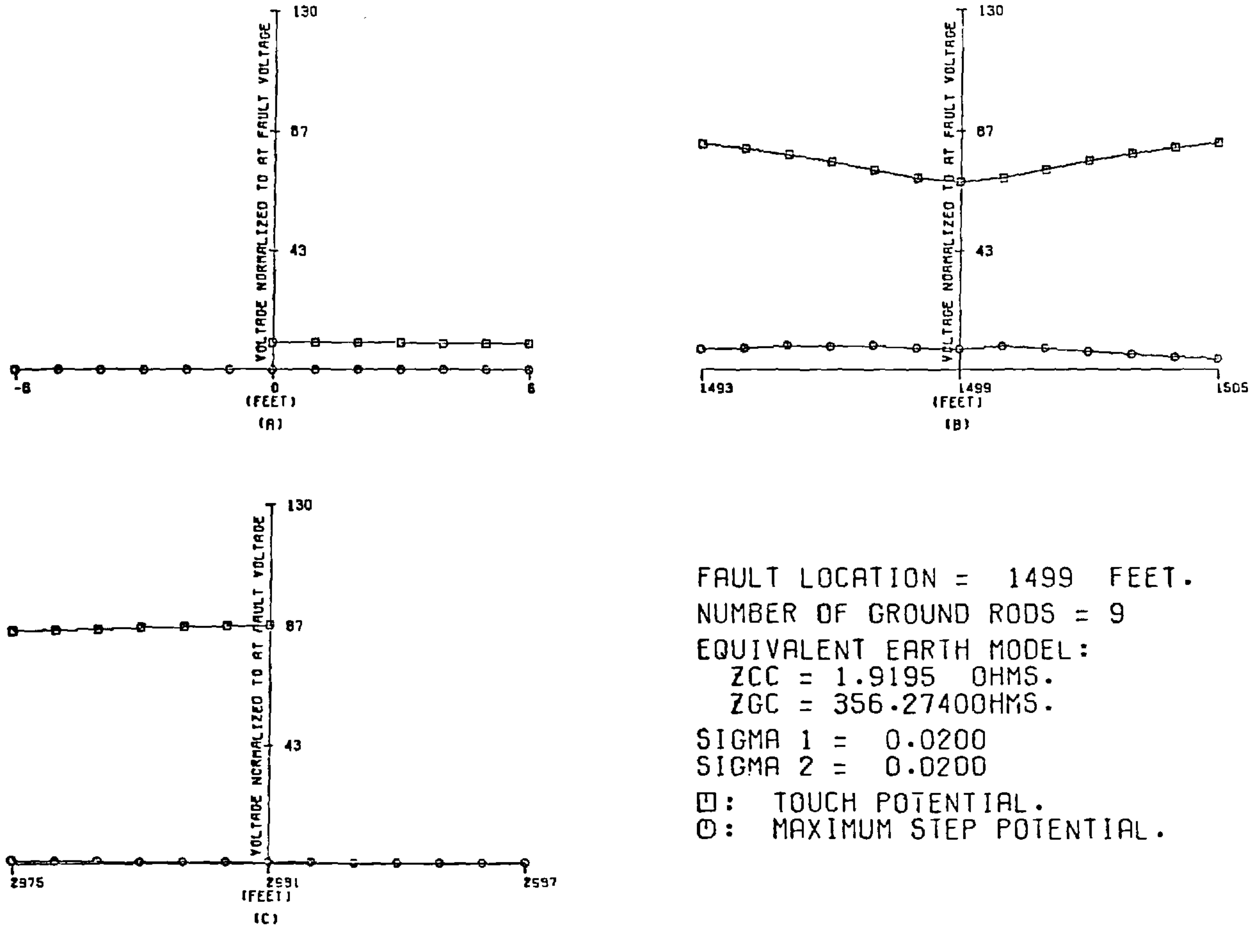
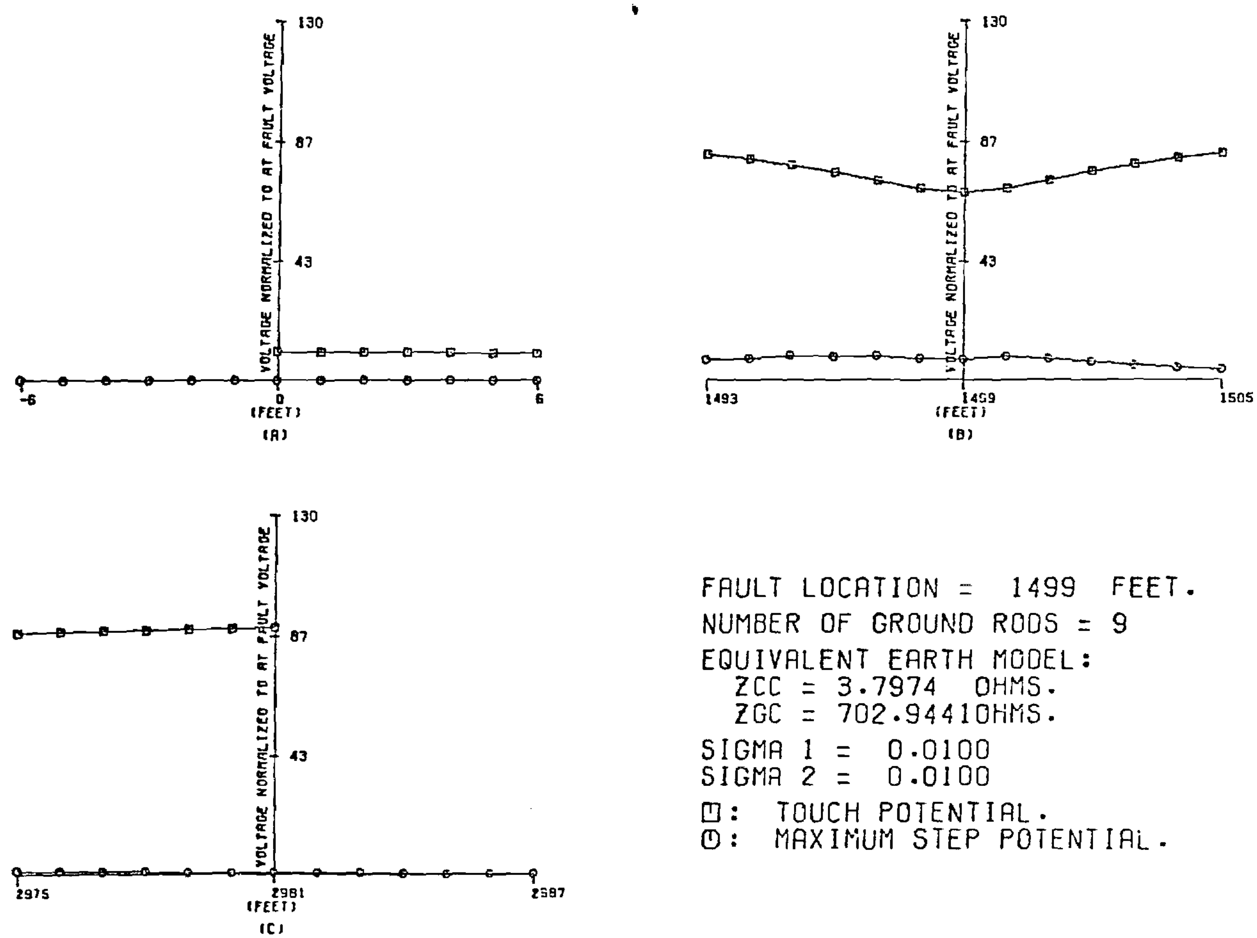
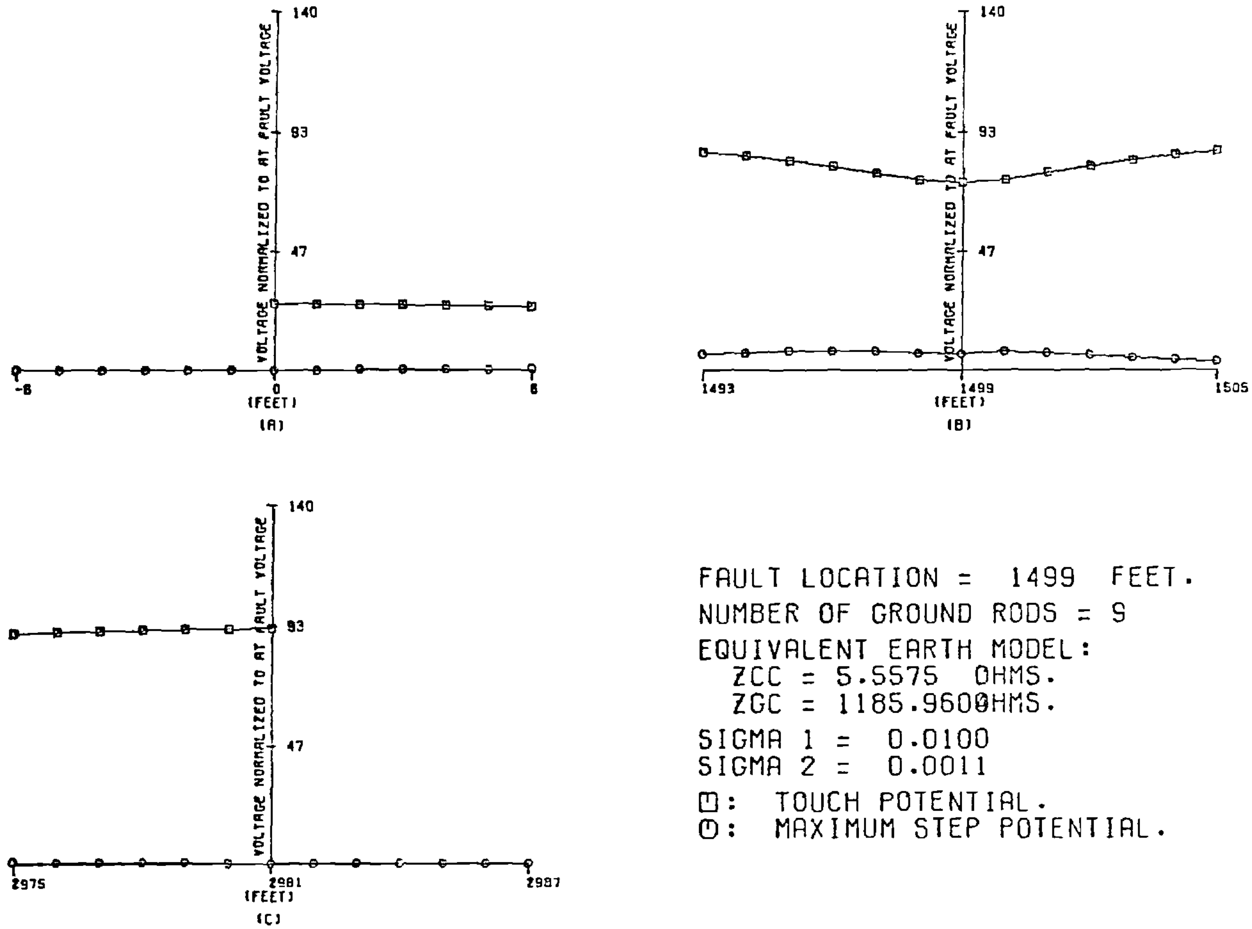


FIGURE A.39. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



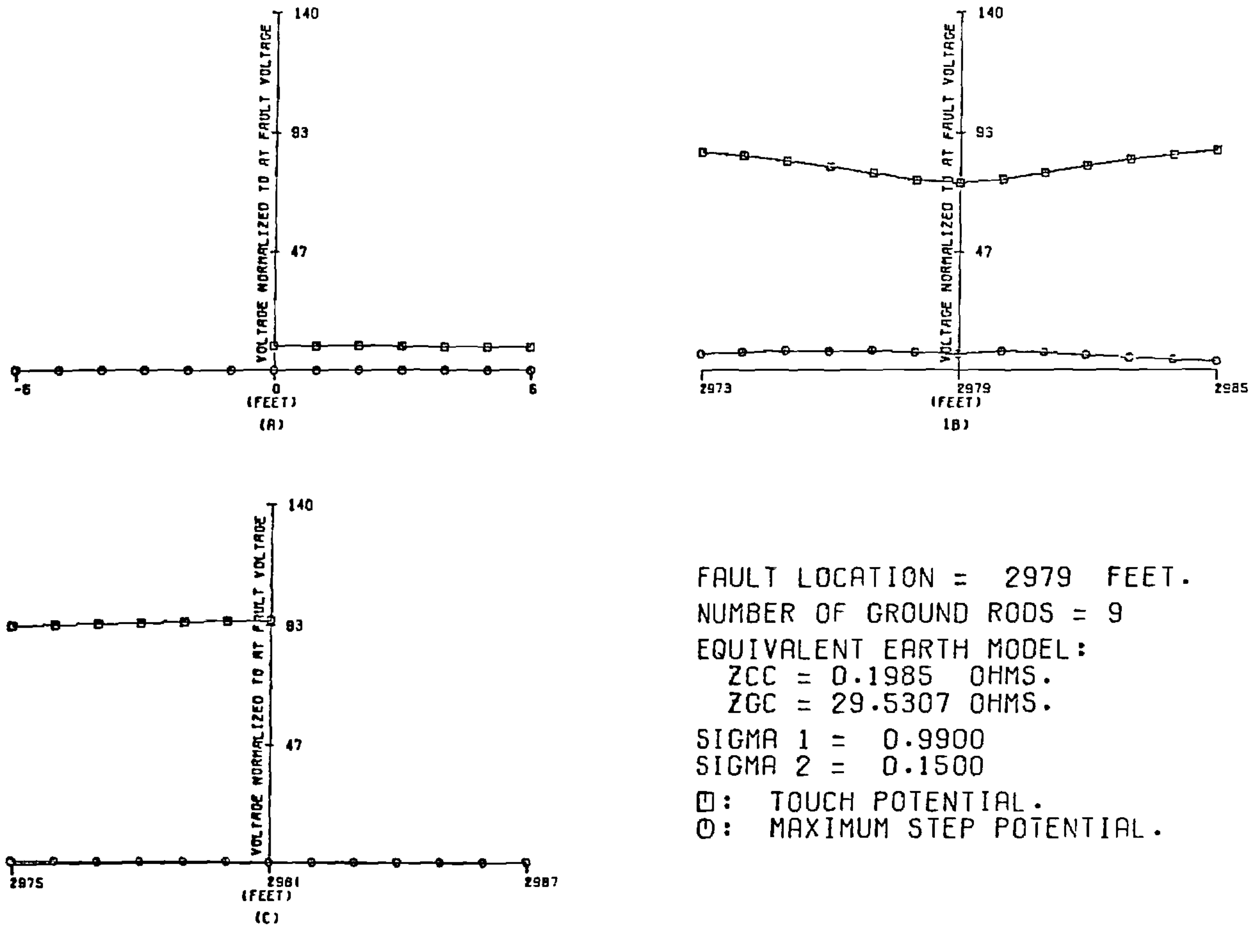
FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 3.7974 OHMS.
ZGC = 702.9441OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE A.40. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 5.5575 OHMS.
ZGC = 1185.960OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.41. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1985 OHMS.
ZGC = 29.5307 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.42. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

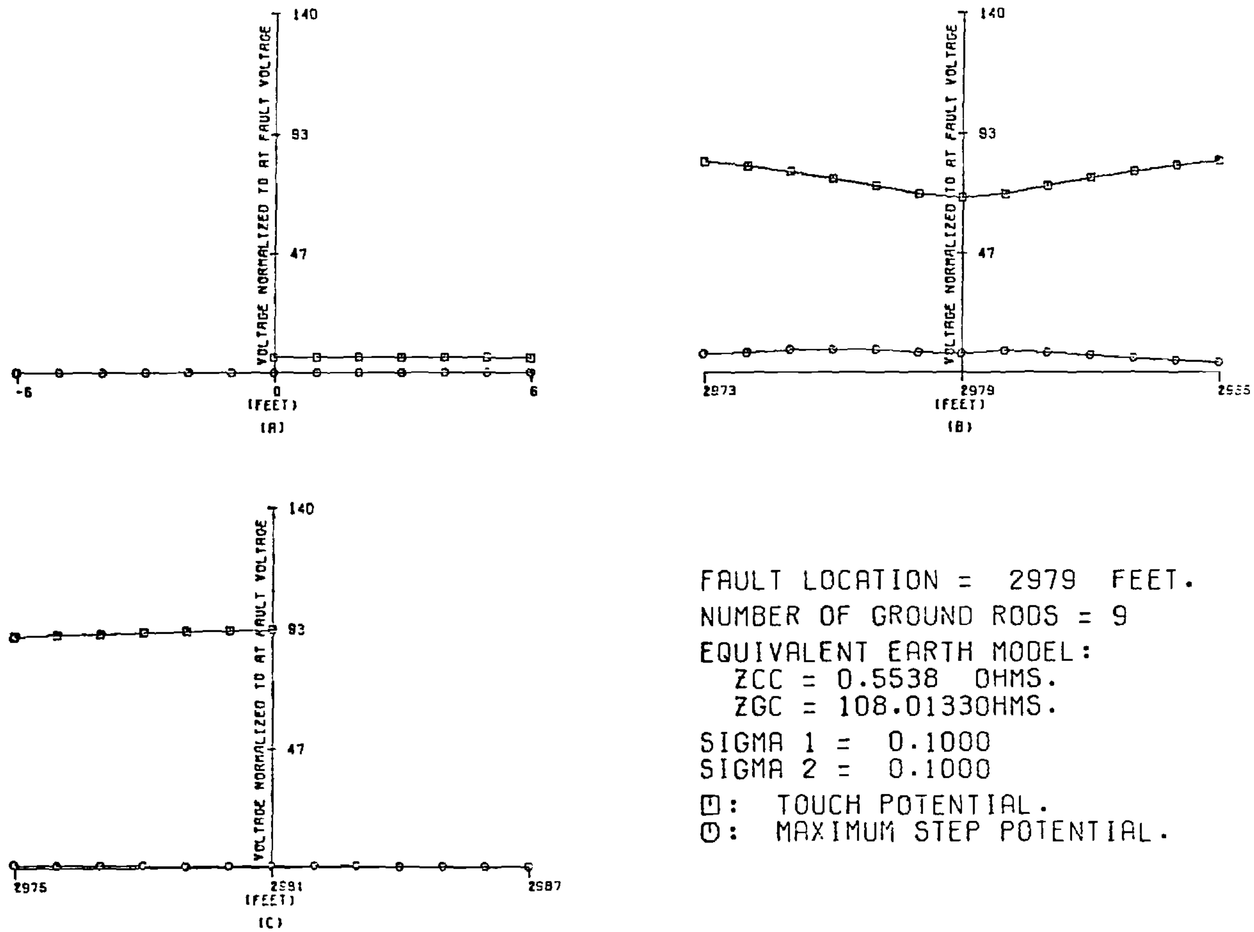


FIGURE A.43. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

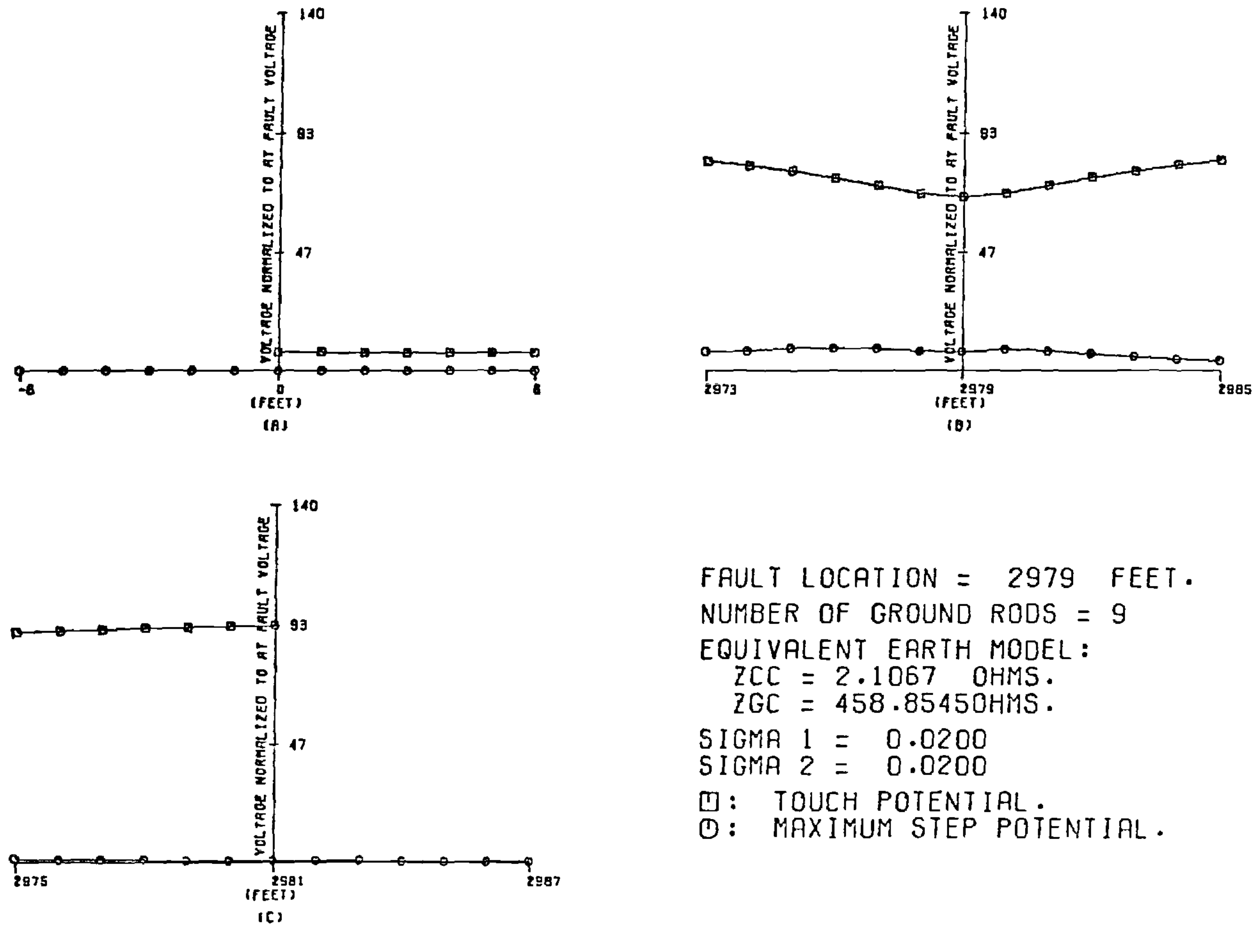


FIGURE A.44. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

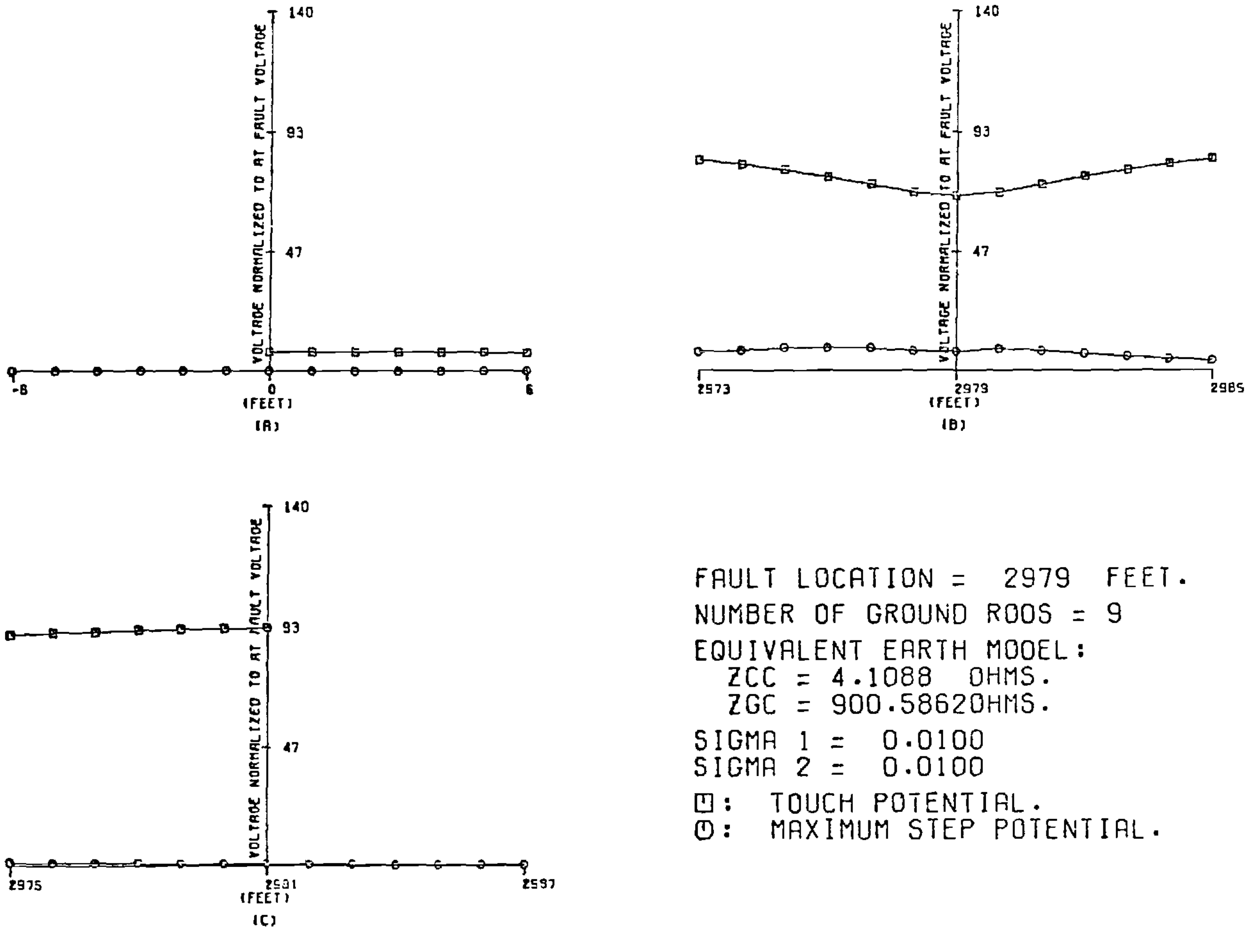
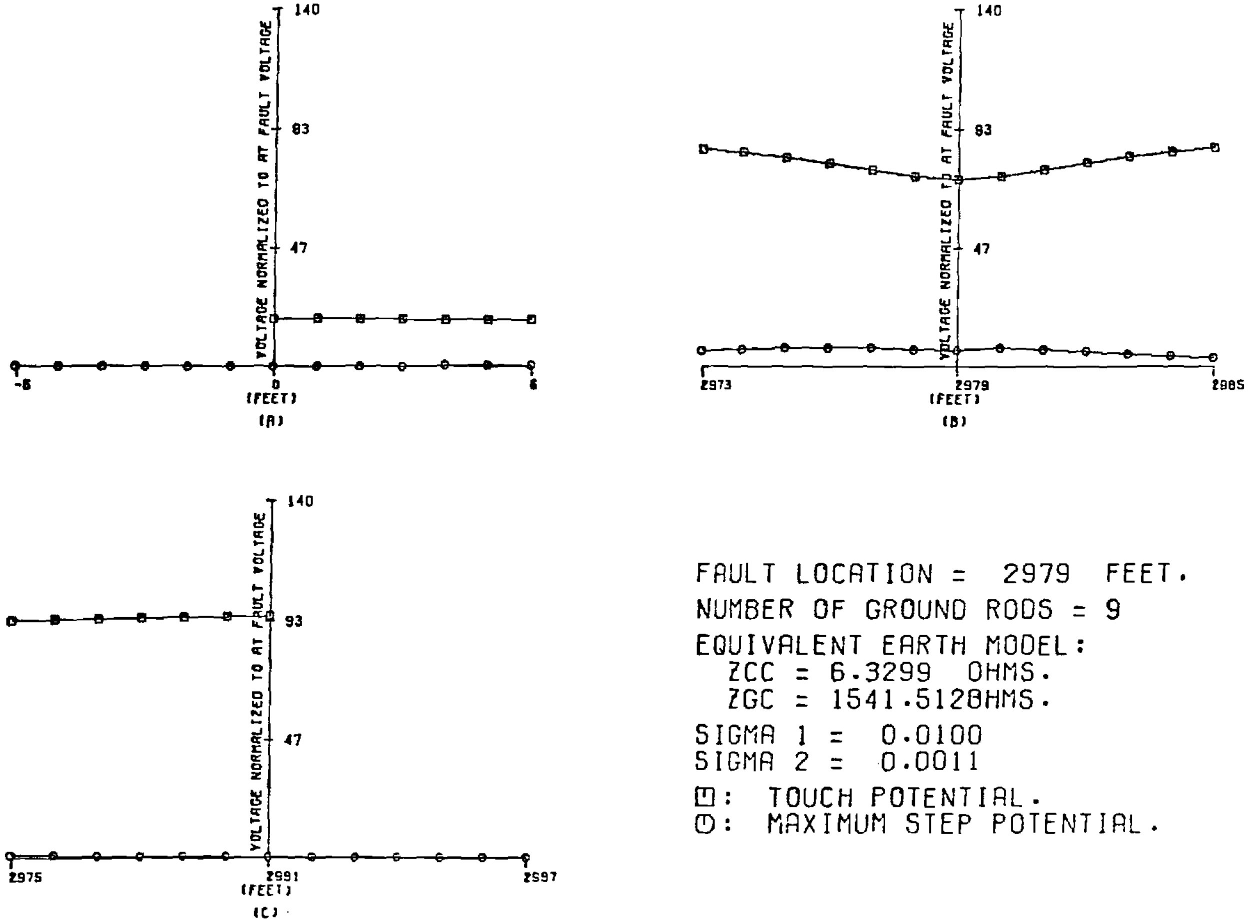
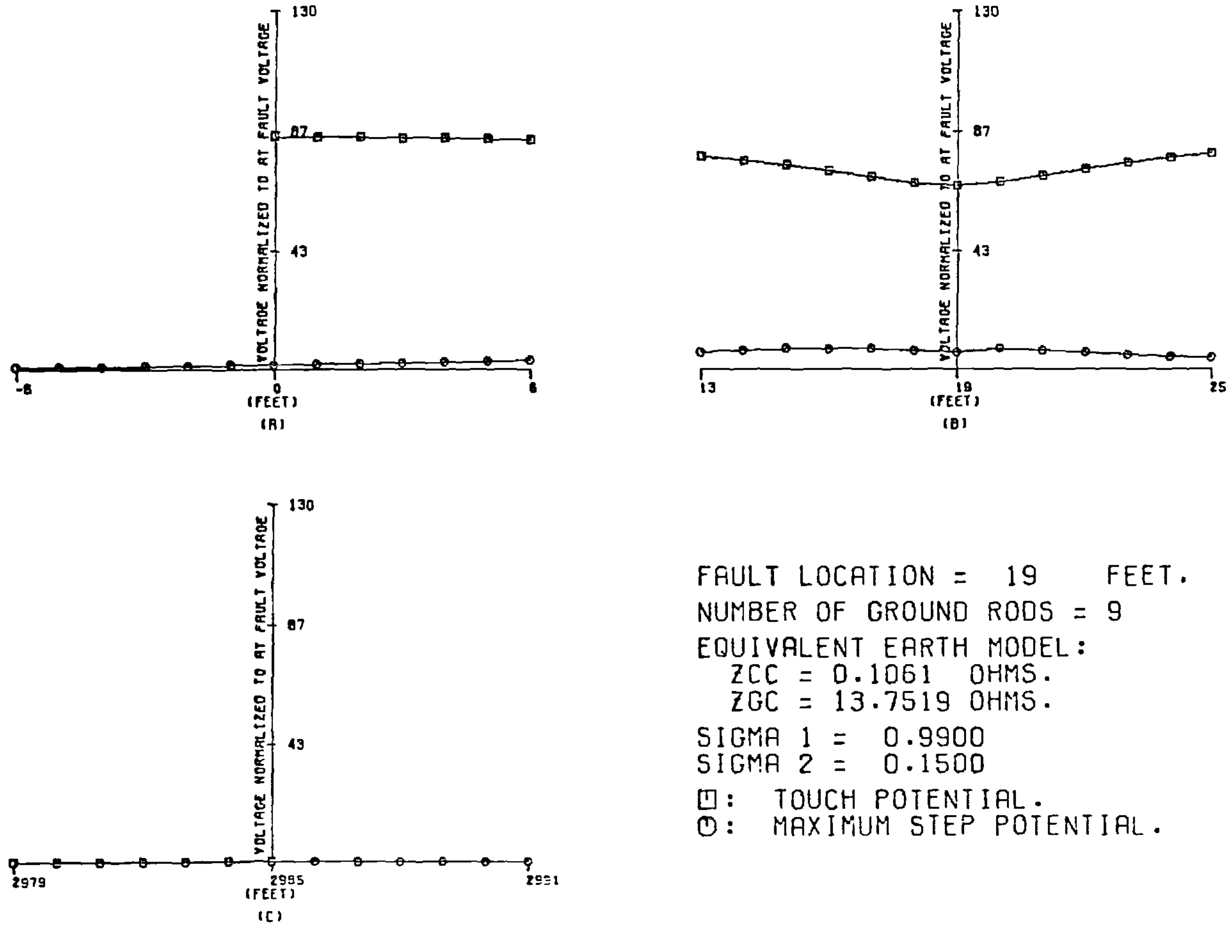


FIGURE A.45. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 6.3299 OHMS.
ZGC = 1541.512OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.46. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
  ZCC = 0.1061 OHMS.
  ZGC = 13.7519 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.47. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

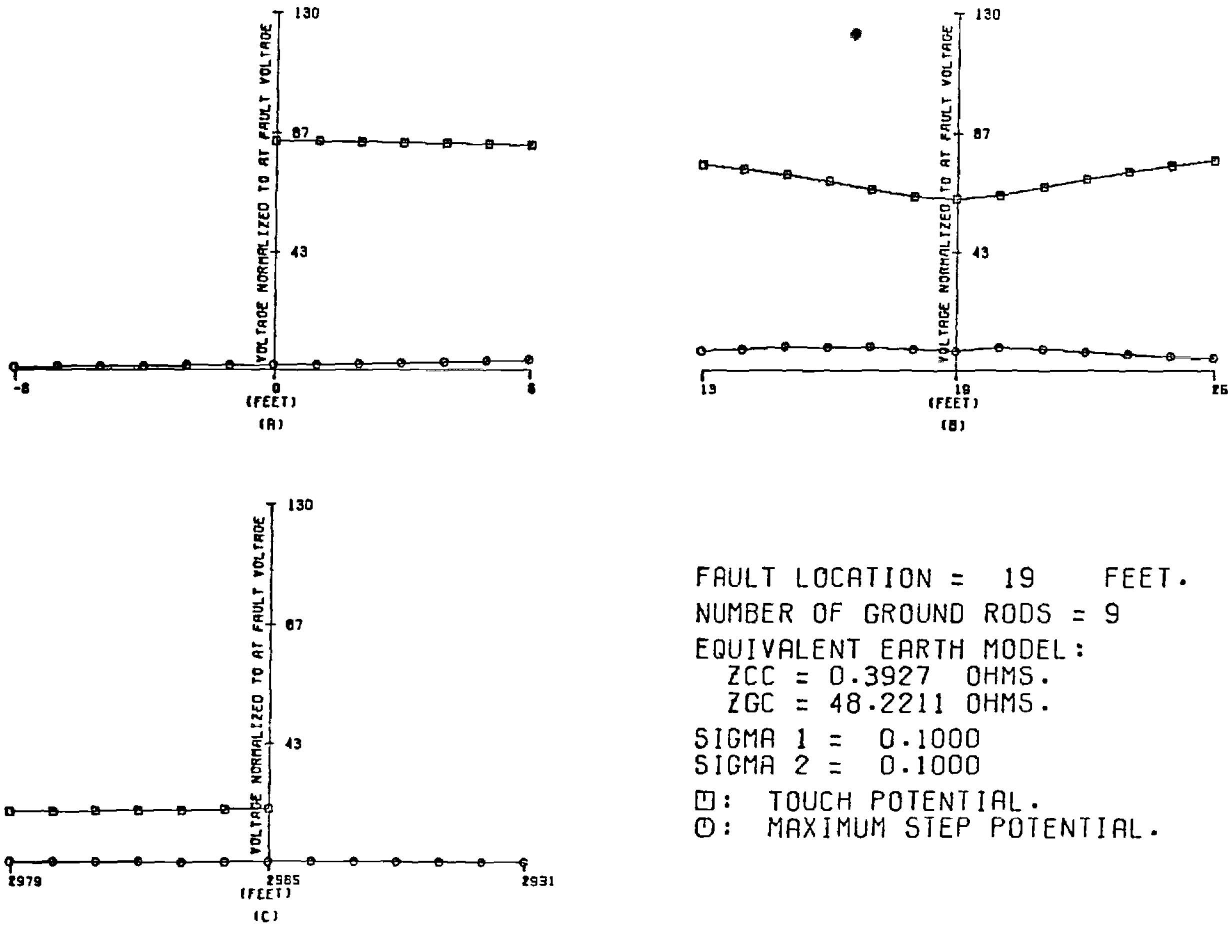


FIGURE A.48. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

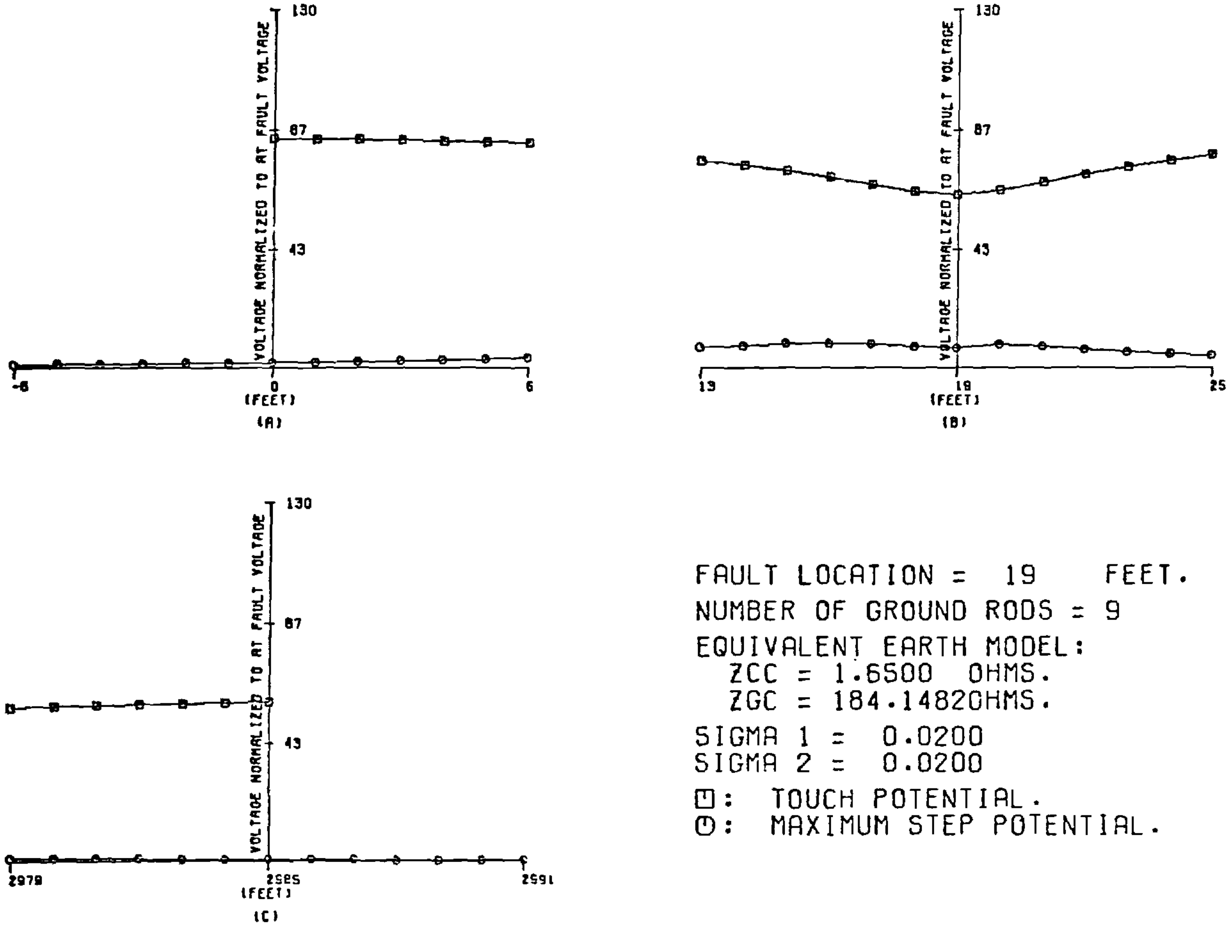
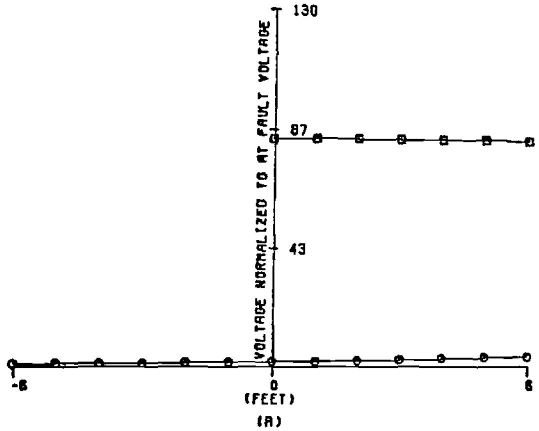
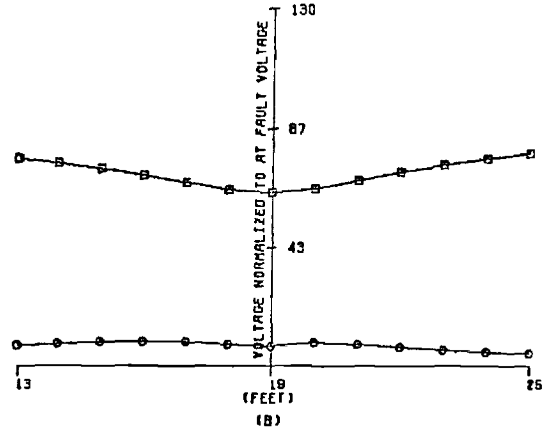
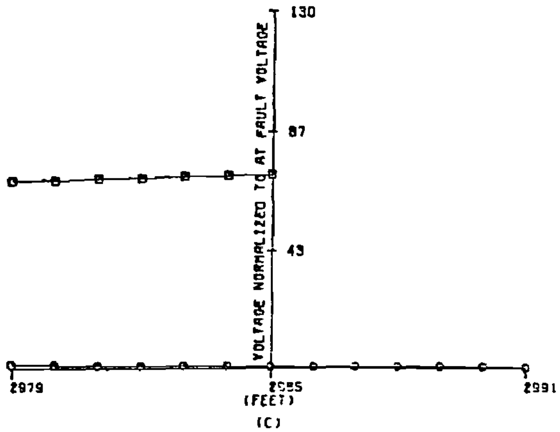


FIGURE A.49. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 3.1791 OHMS.
ZGC = 348.5917OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE A.50. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

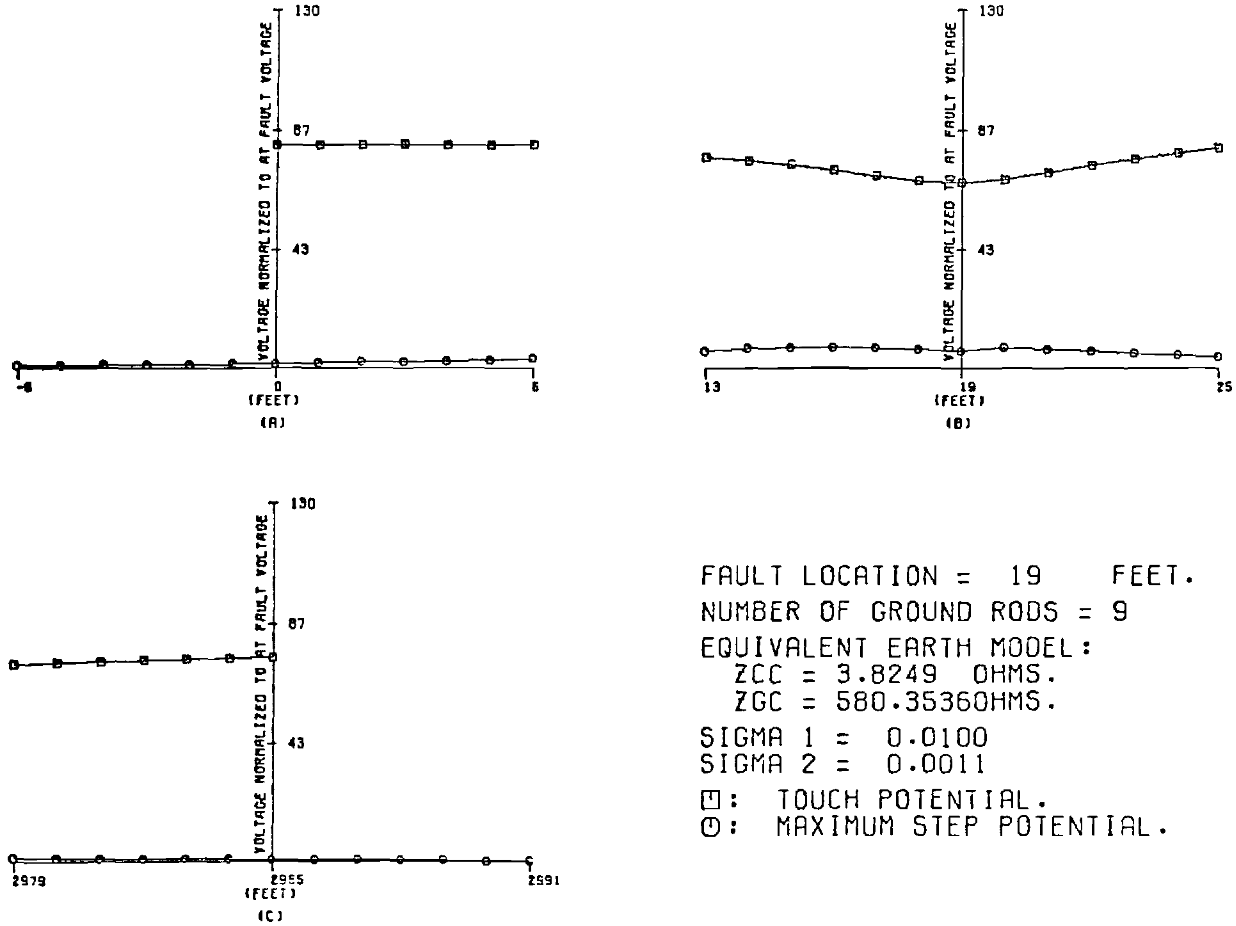
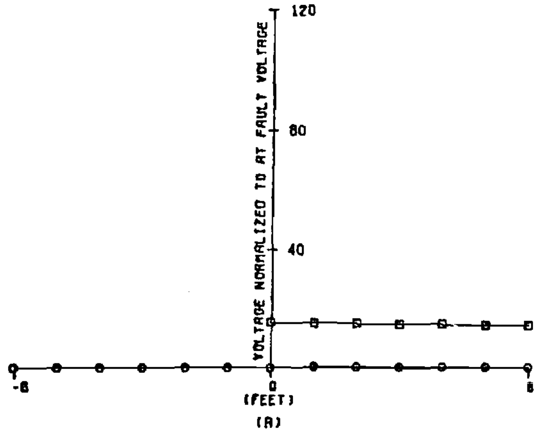
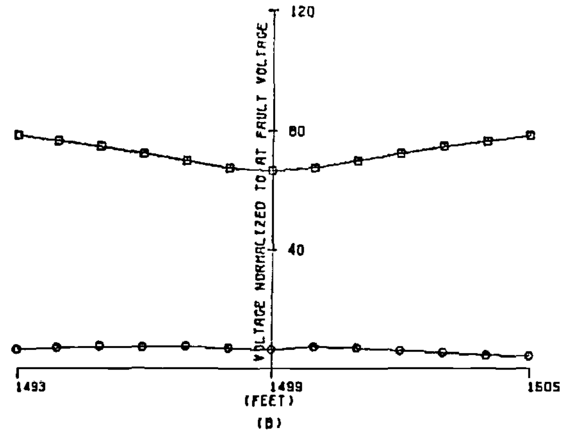
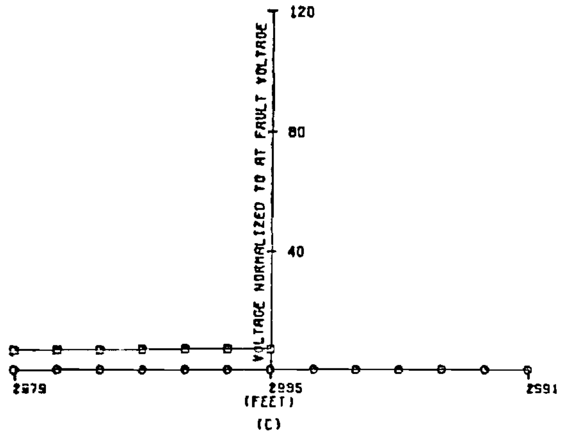


FIGURE A.51. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.0979 OHMS.
ZGC = 12.2214 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.52. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

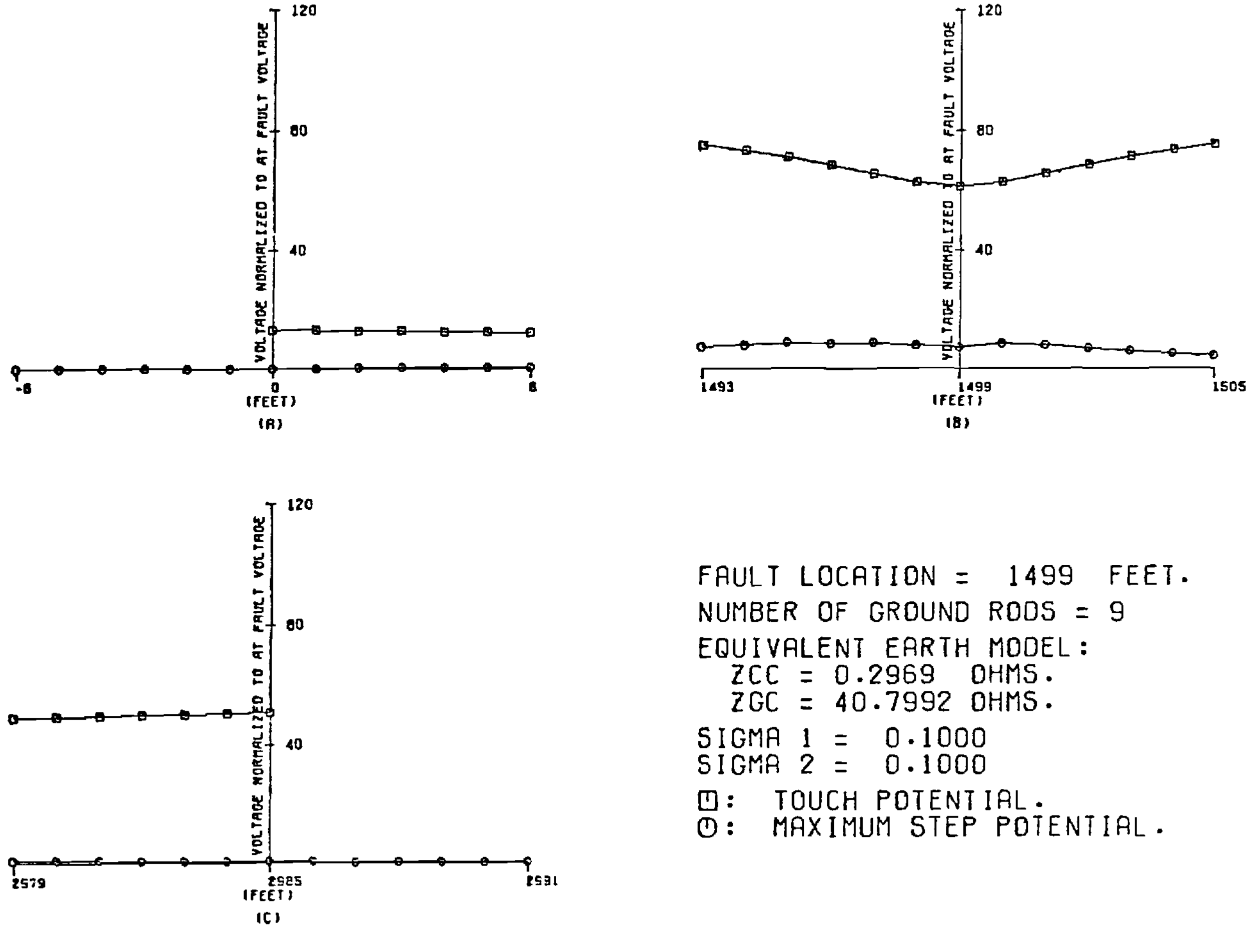


FIGURE A.53. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

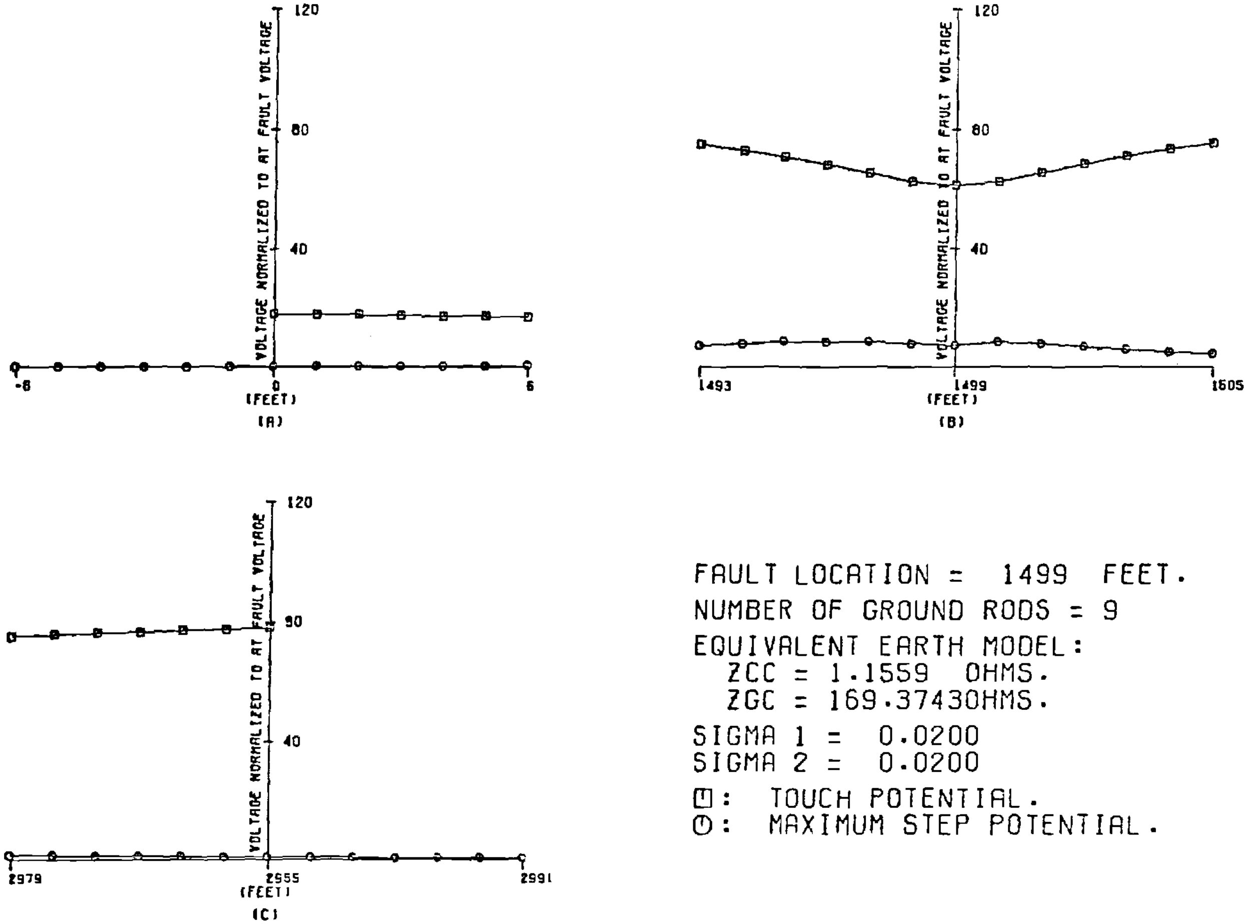
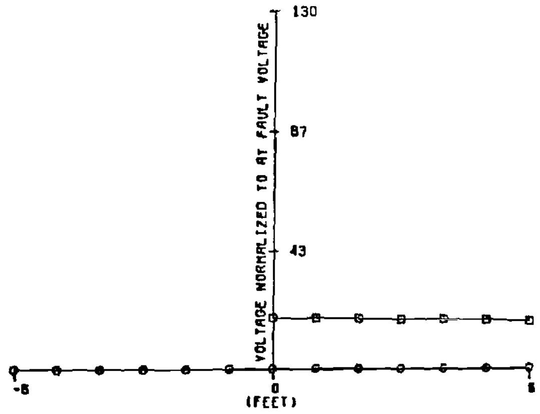
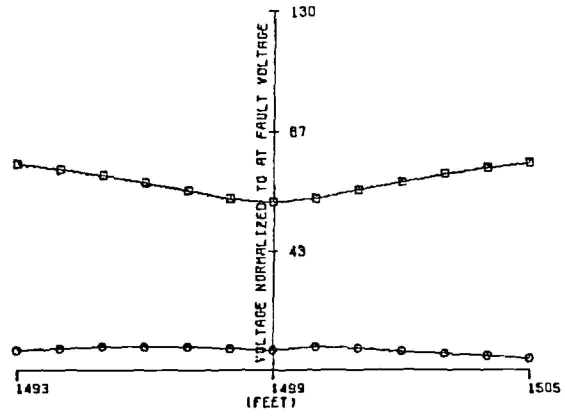
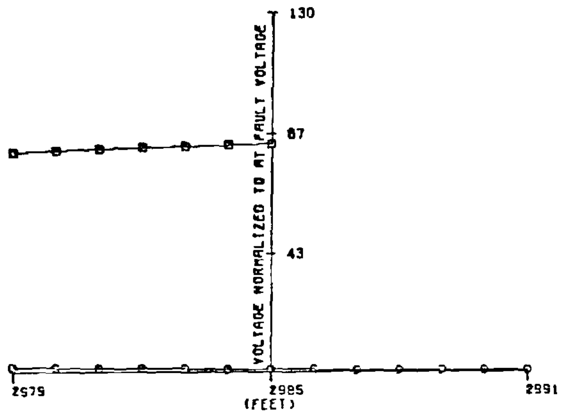


FIGURE A.54. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 2.2620 OHMS.
ZGC = 331.4221OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE A.55. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

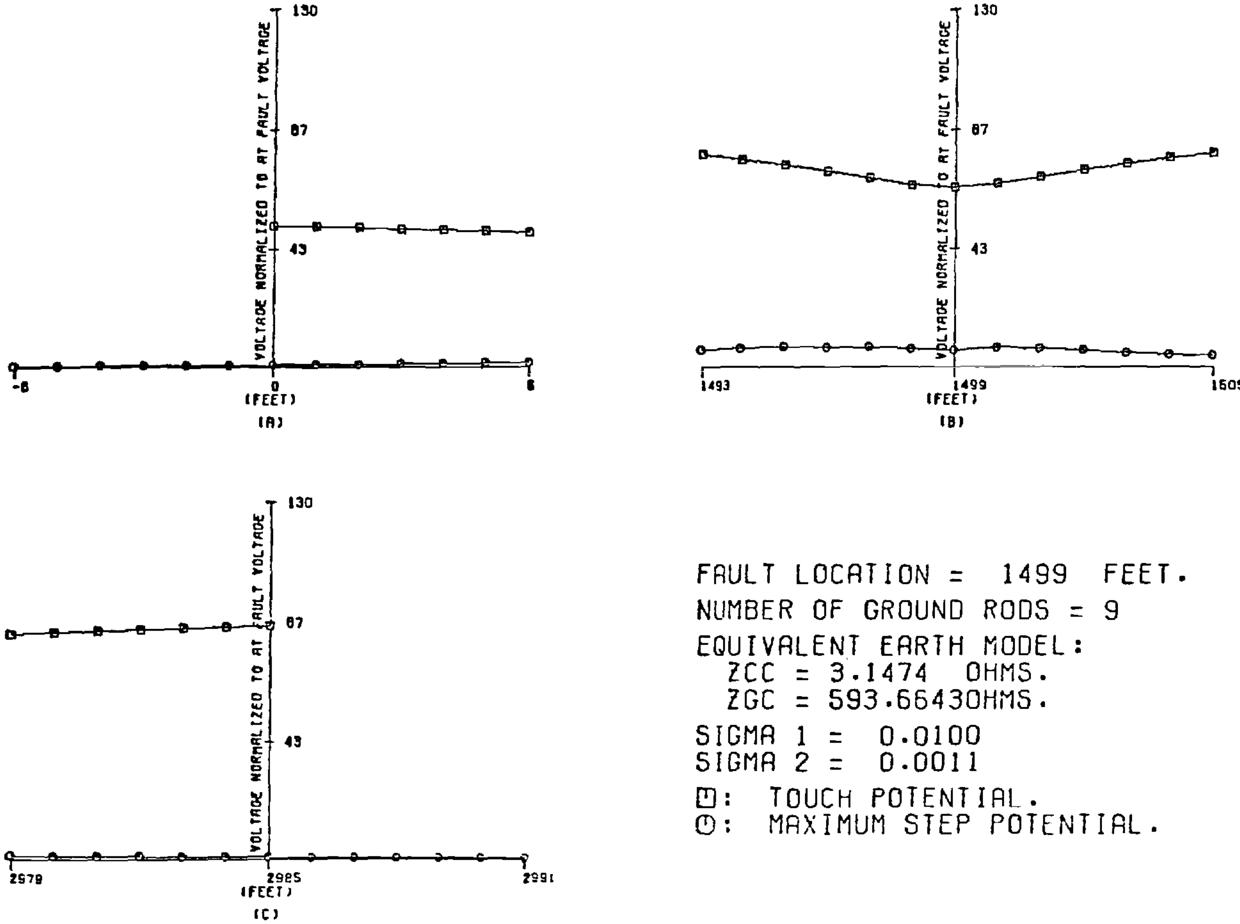


FIGURE A.56. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

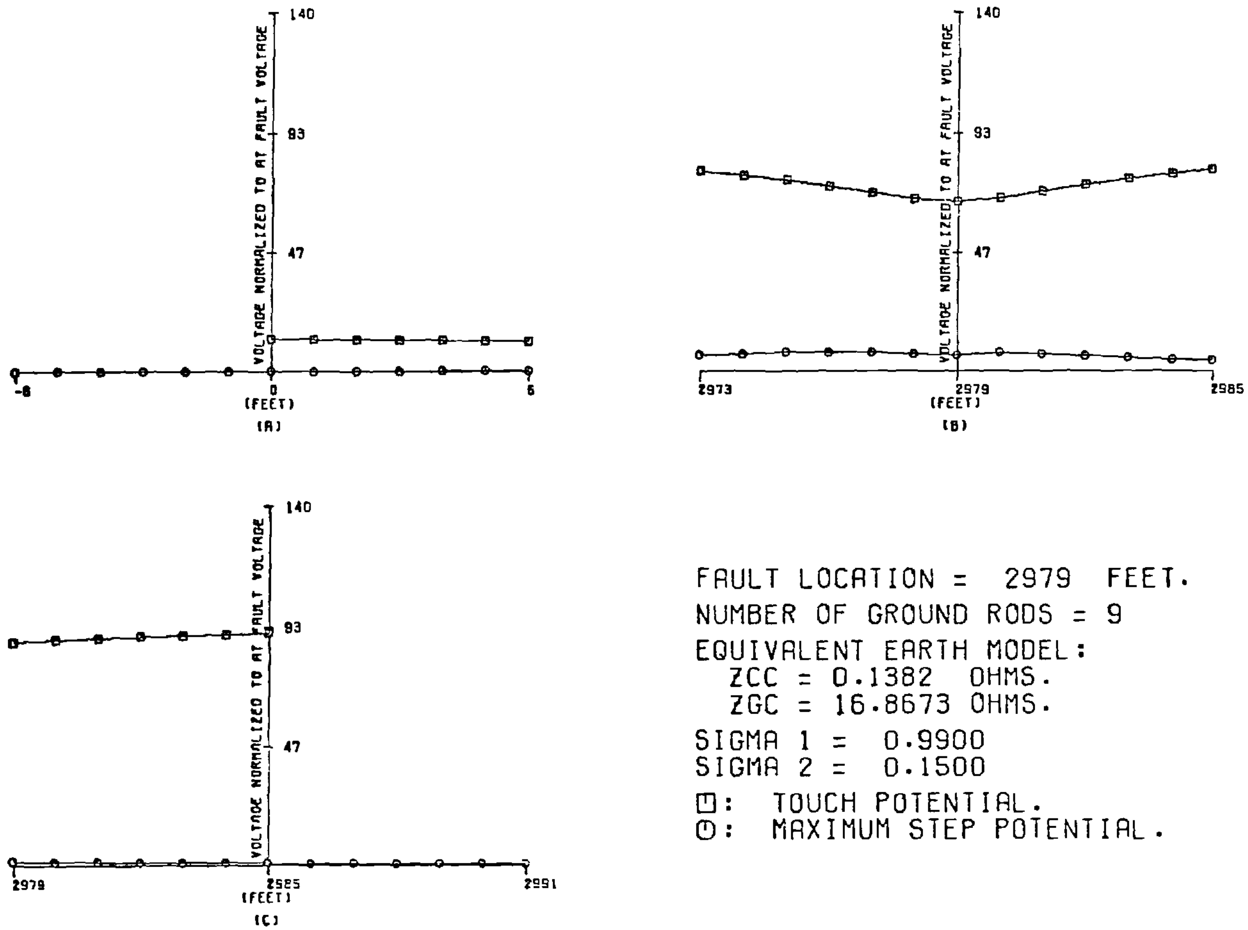
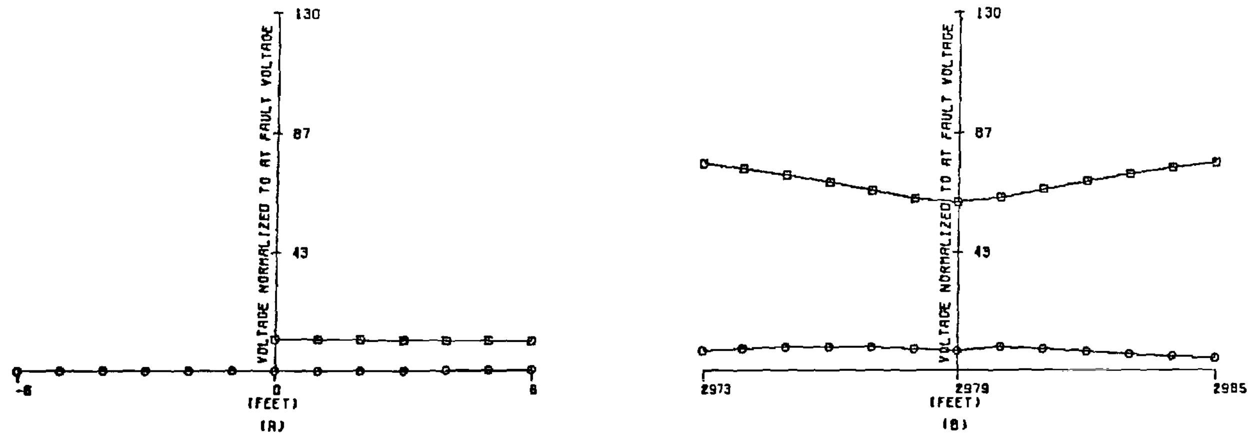
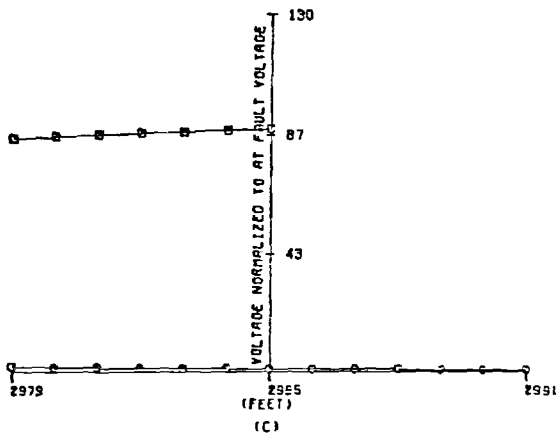


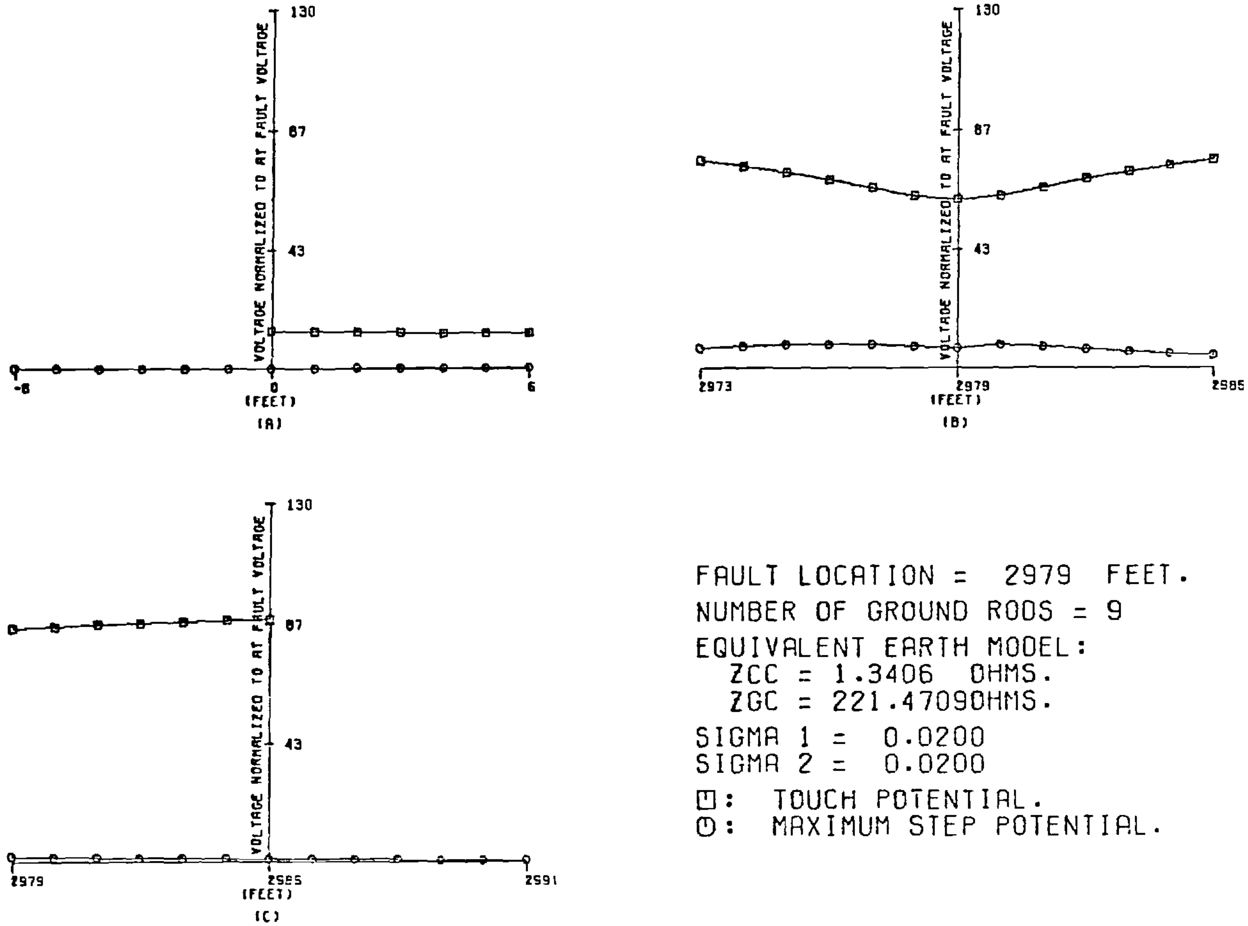
FIGURE A.57. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.4008 OHMS.
ZGC = 56.3183 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.59. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 1.3406 OHMS.
ZGC = 221.4709OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.59. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

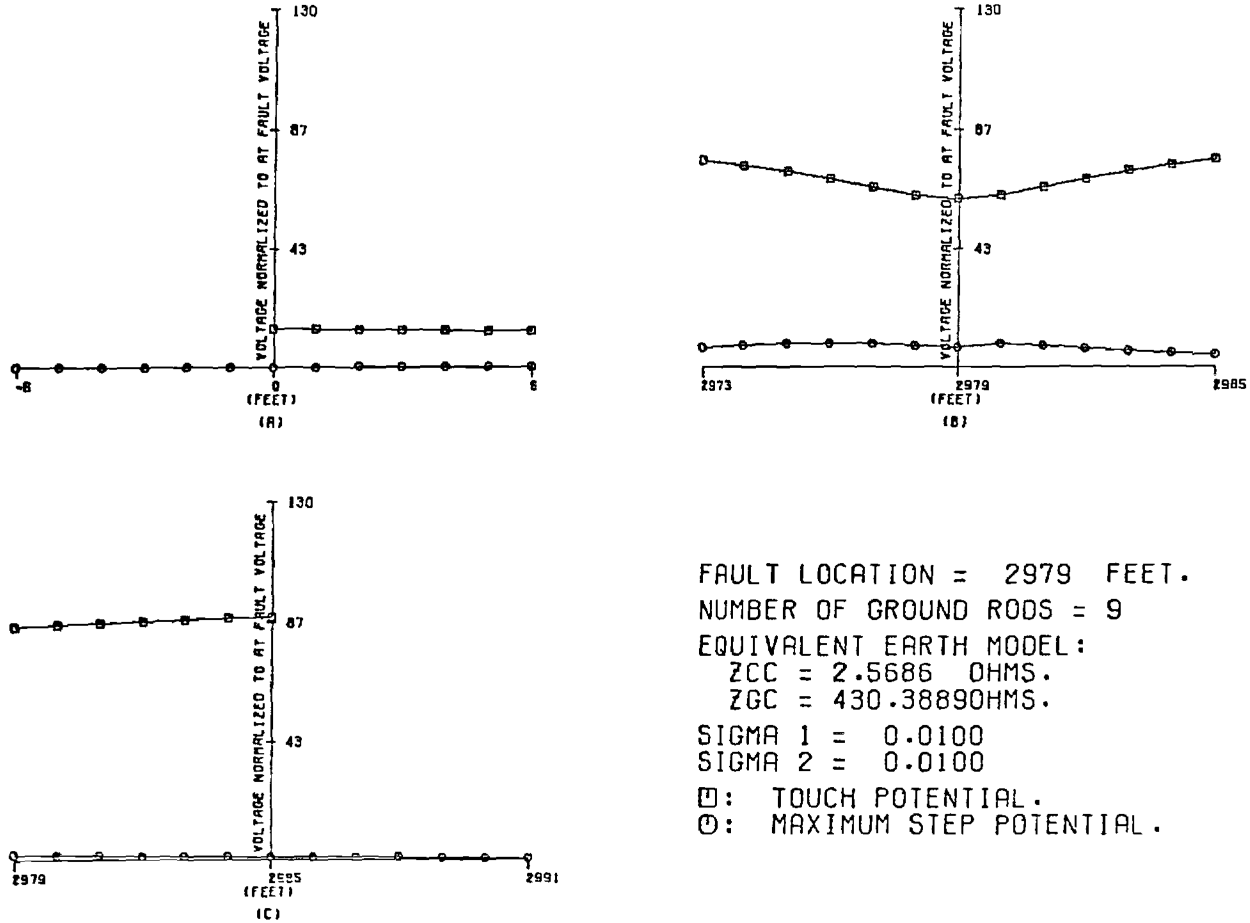
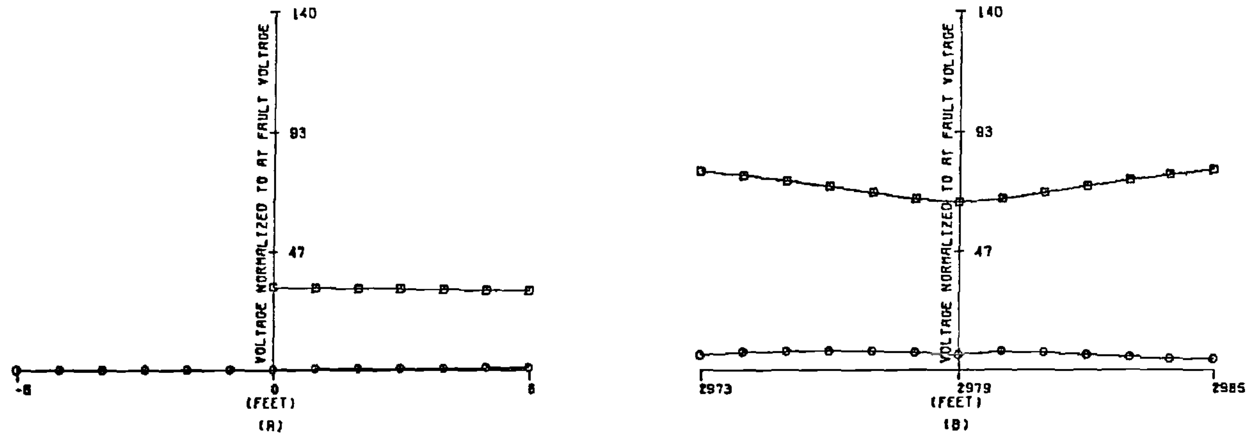
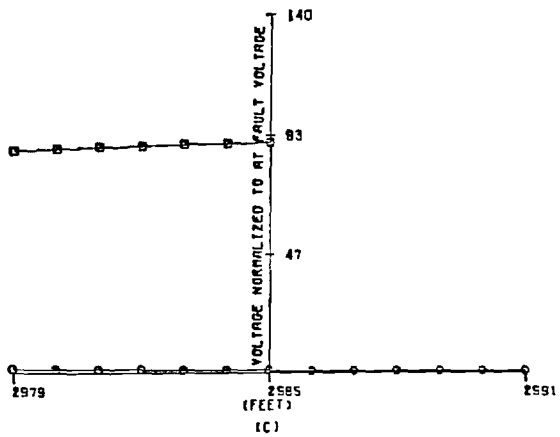


FIGURE A.60. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 3.9208 OHMS.
ZGC = 793.4076OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE A.61. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

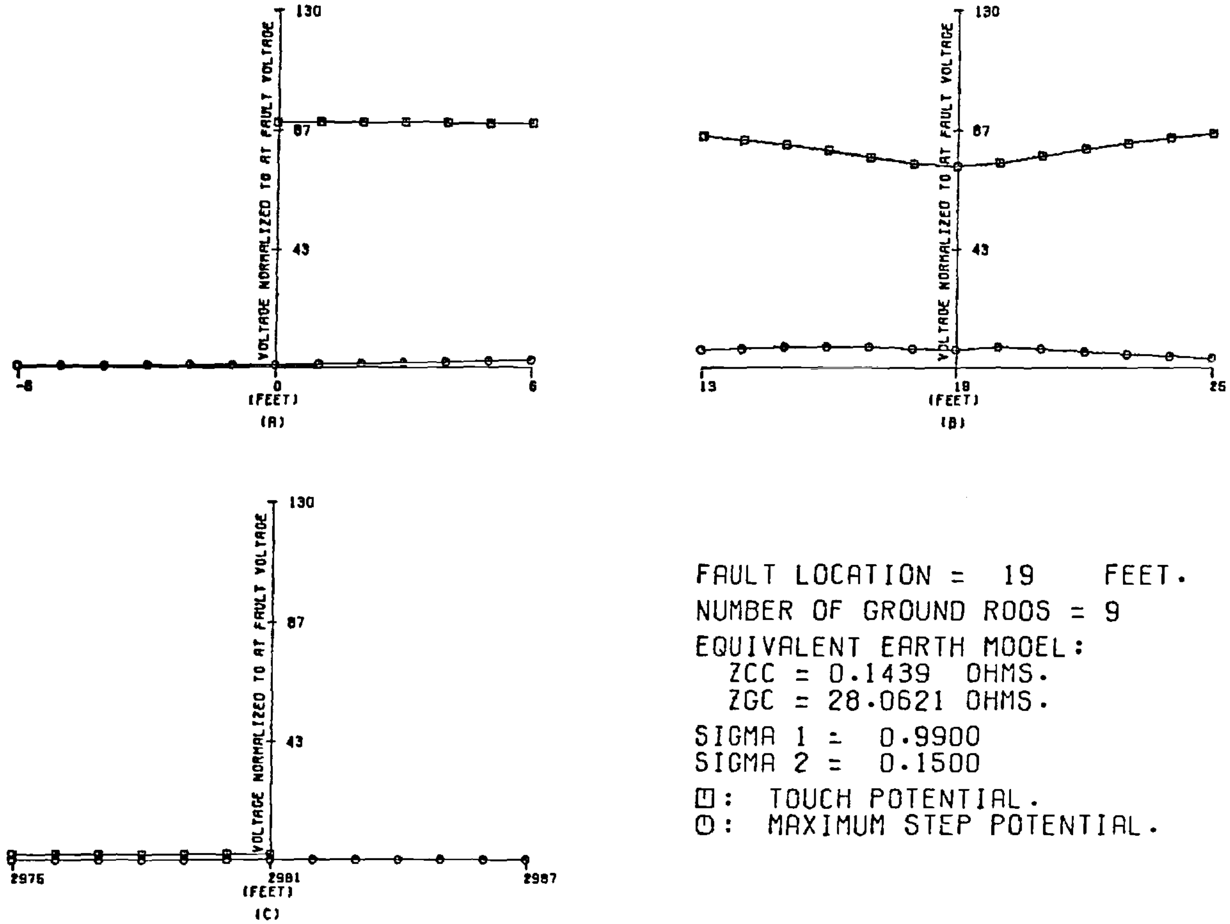
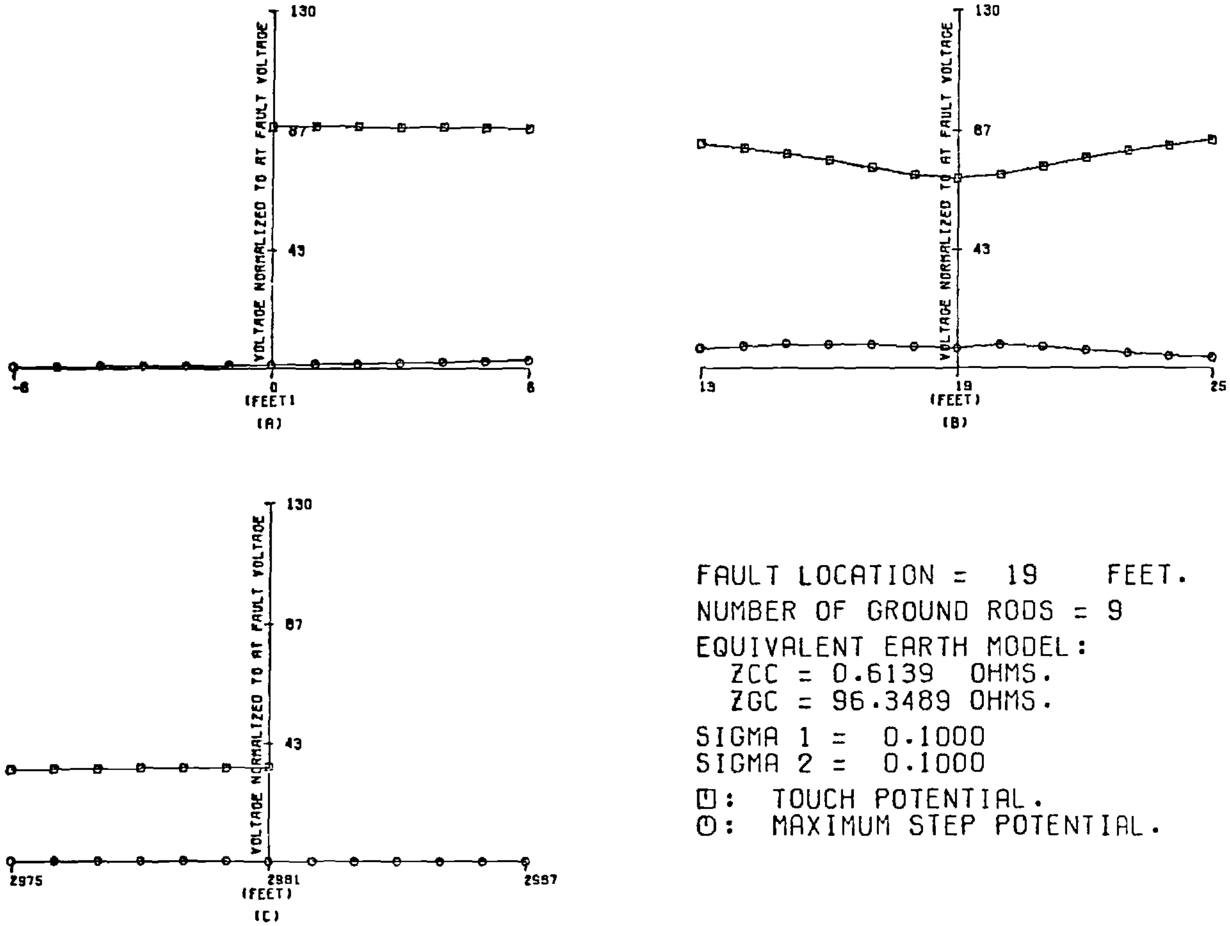


FIGURE A.62. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.6139 OHMS.
ZGC = 96.3489 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.63. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

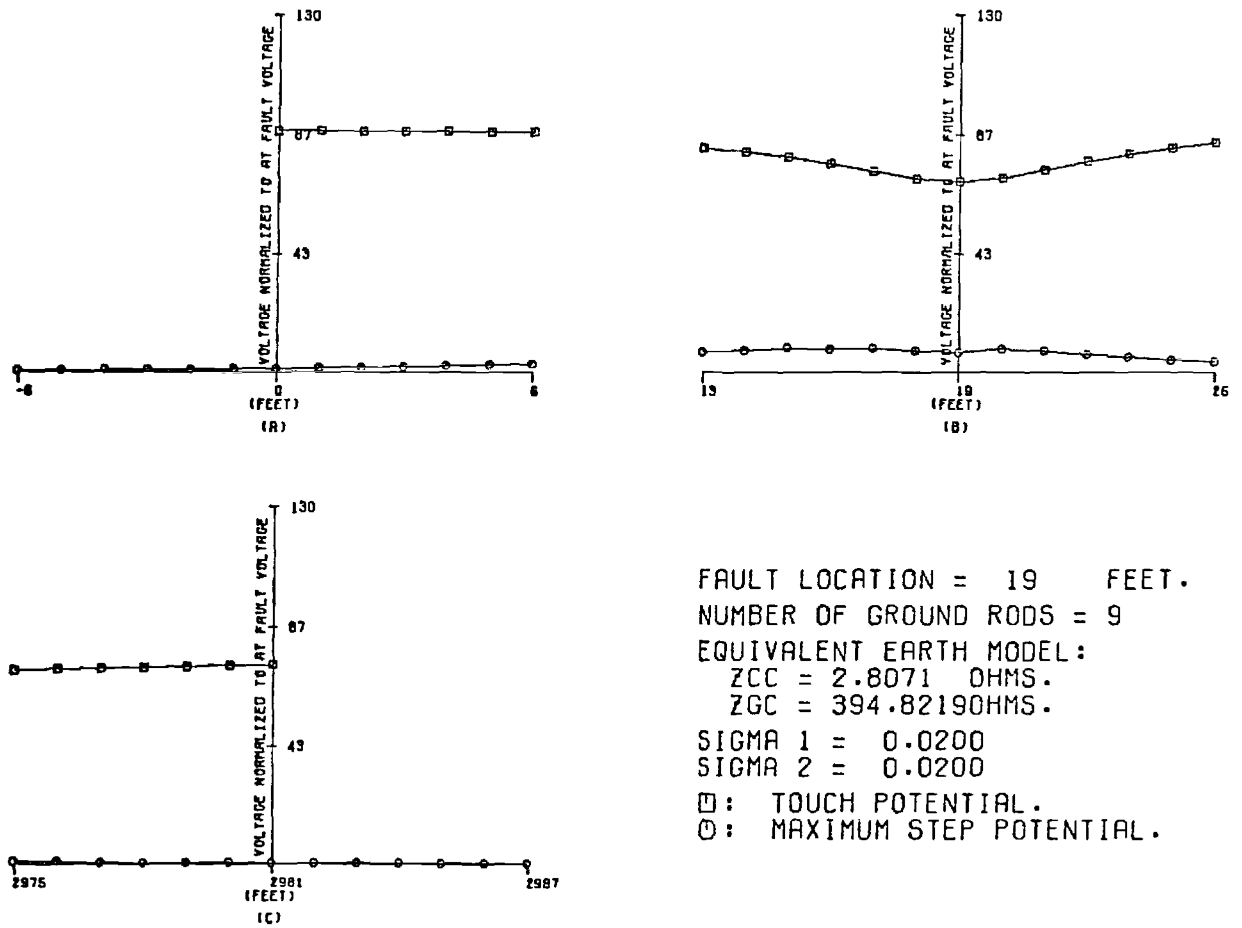


FIGURE A.64. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

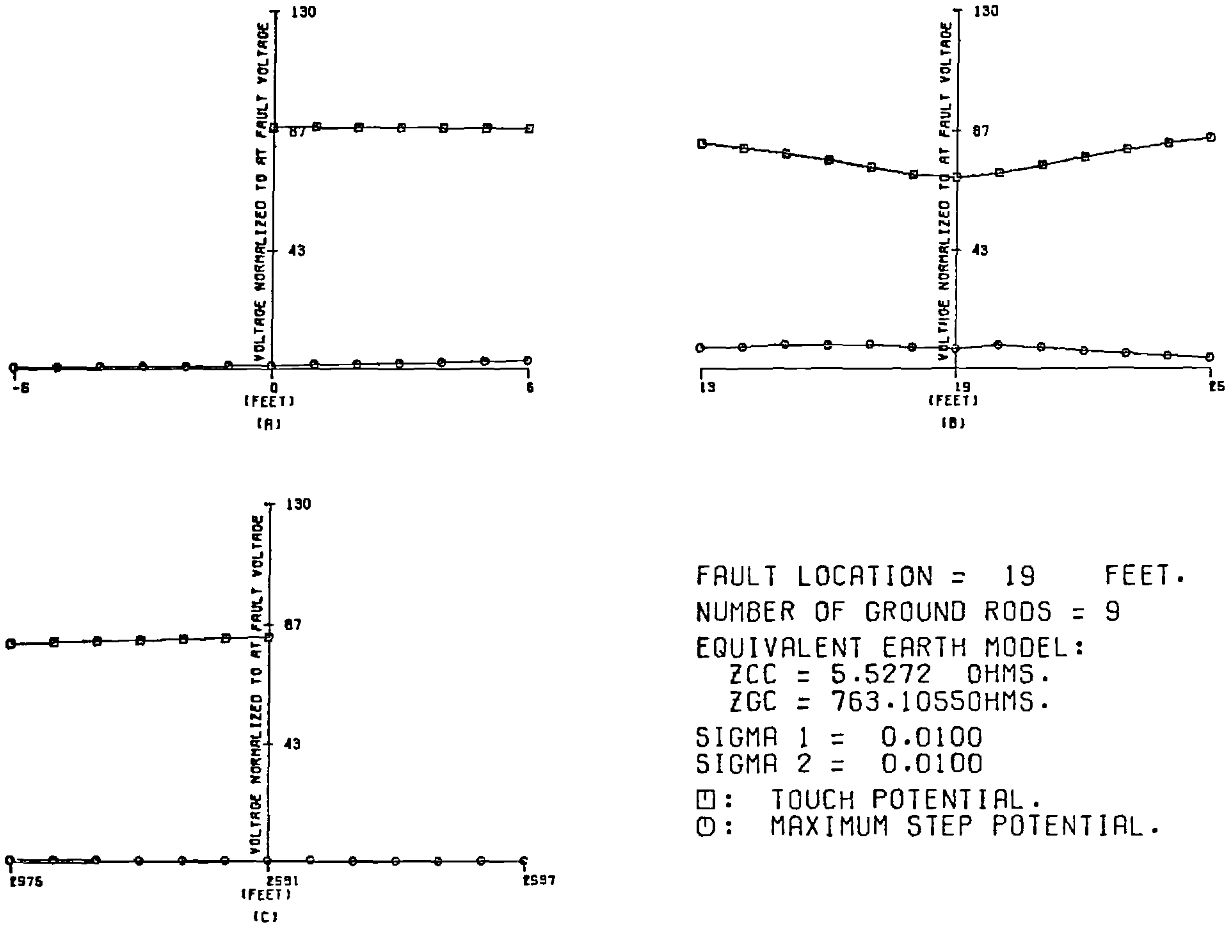


FIGURE A.65. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

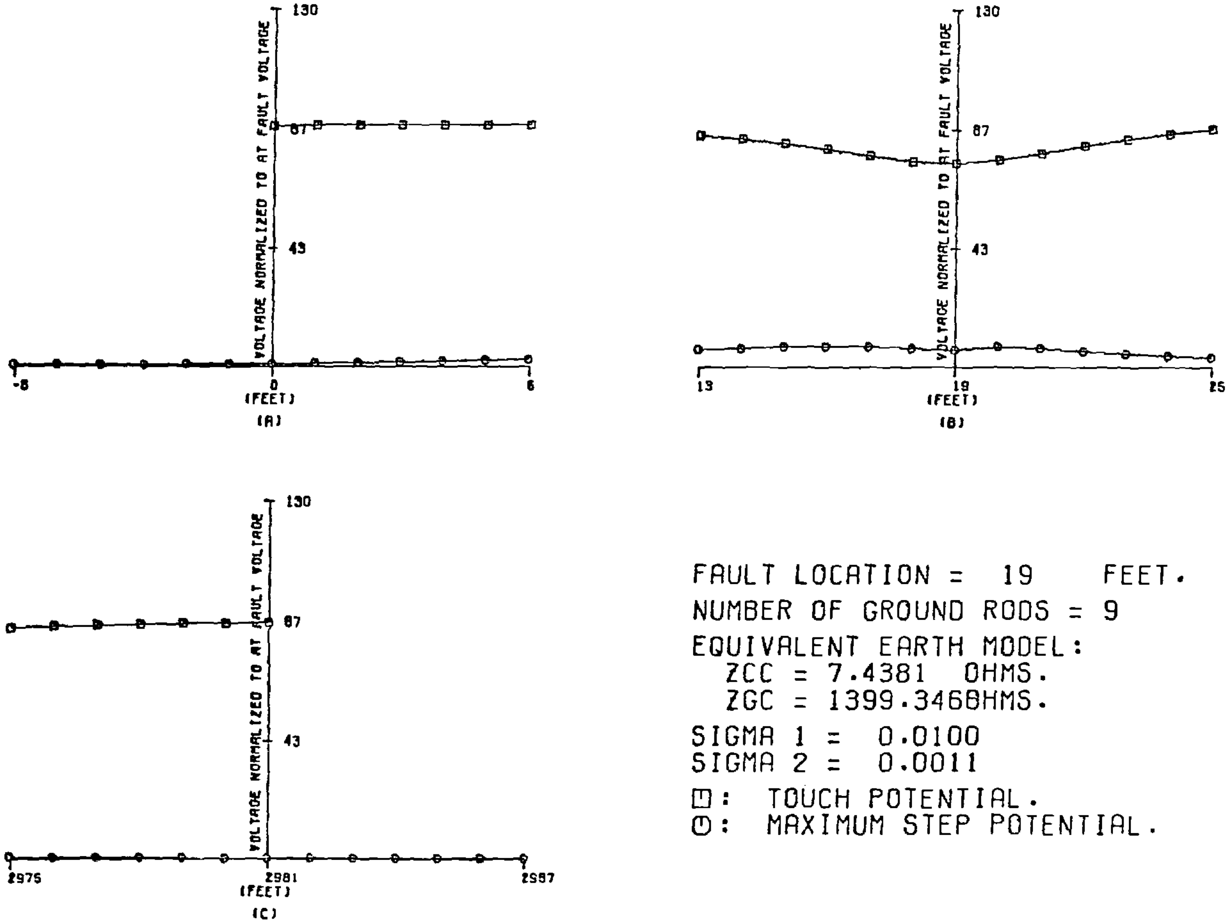
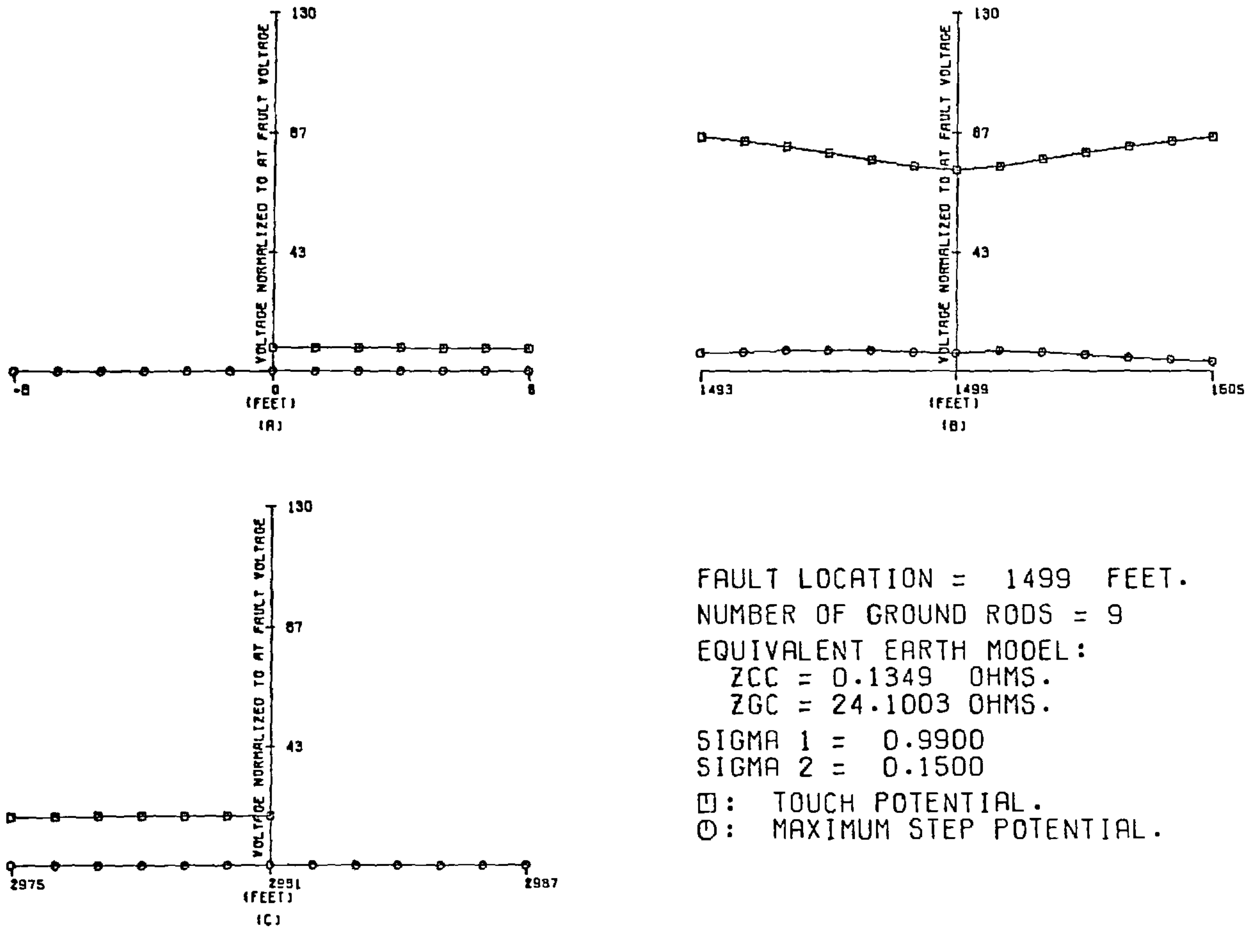


FIGURE A.66. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1349 OHMS.
ZGC = 24.1003 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.67. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

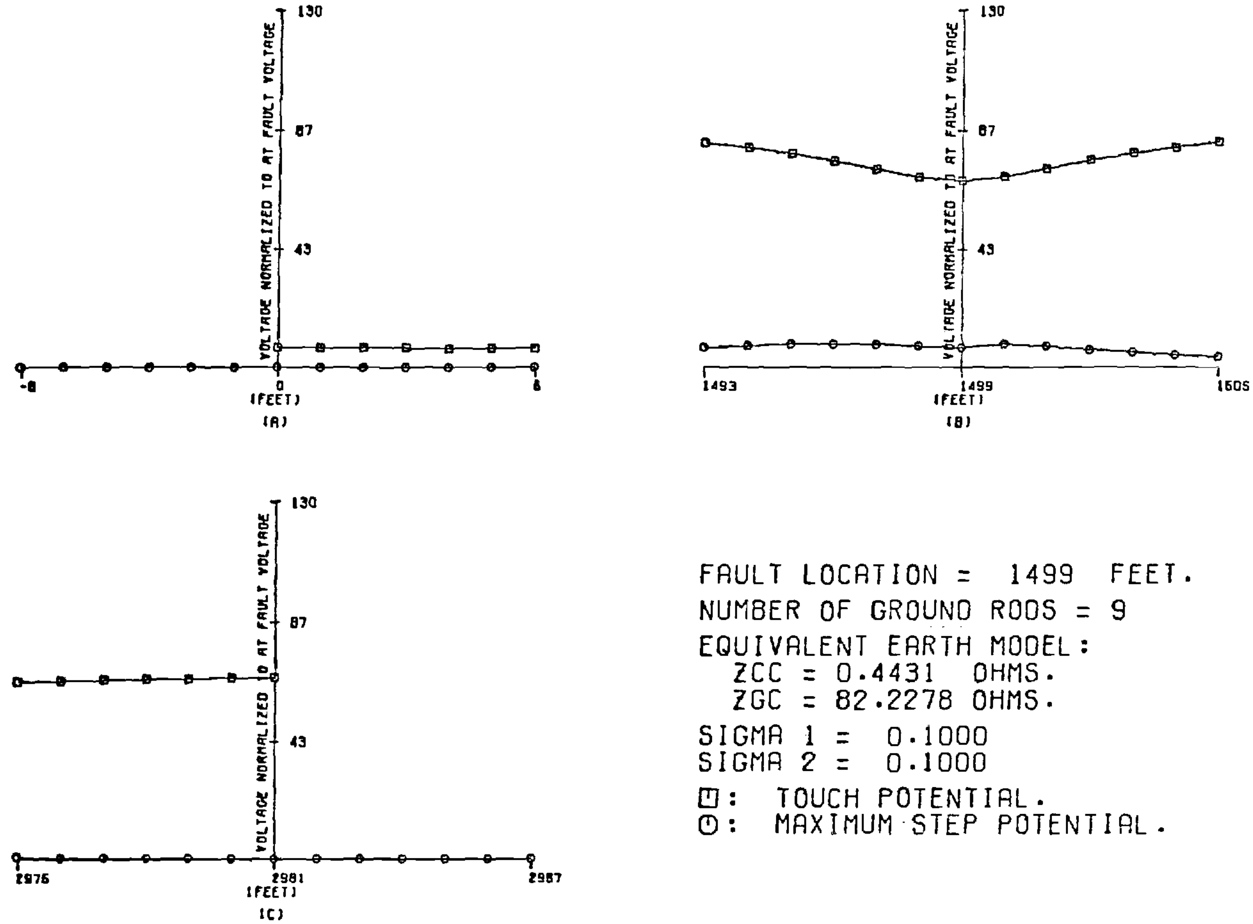


FIGURE A.68. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

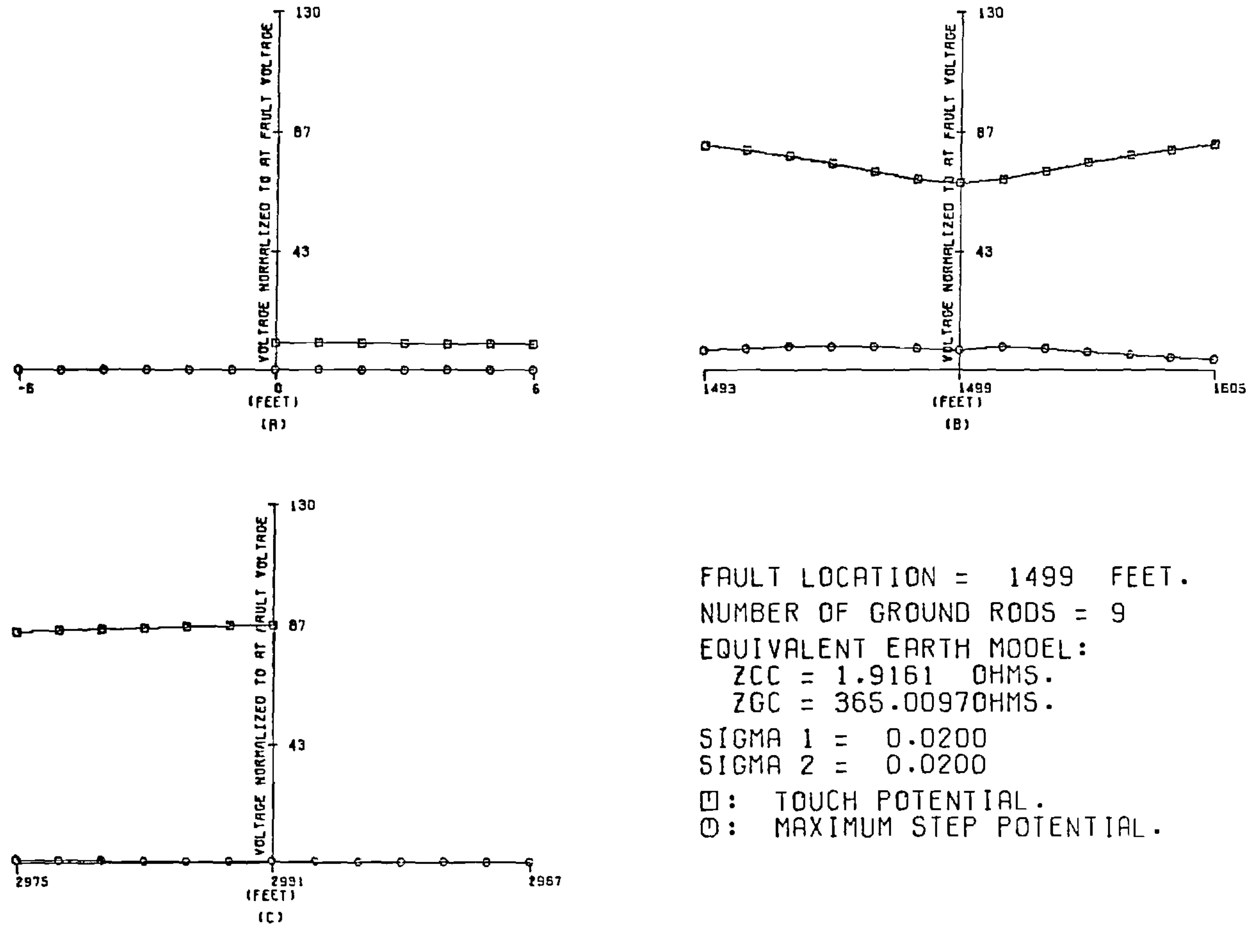


FIGURE A.69. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

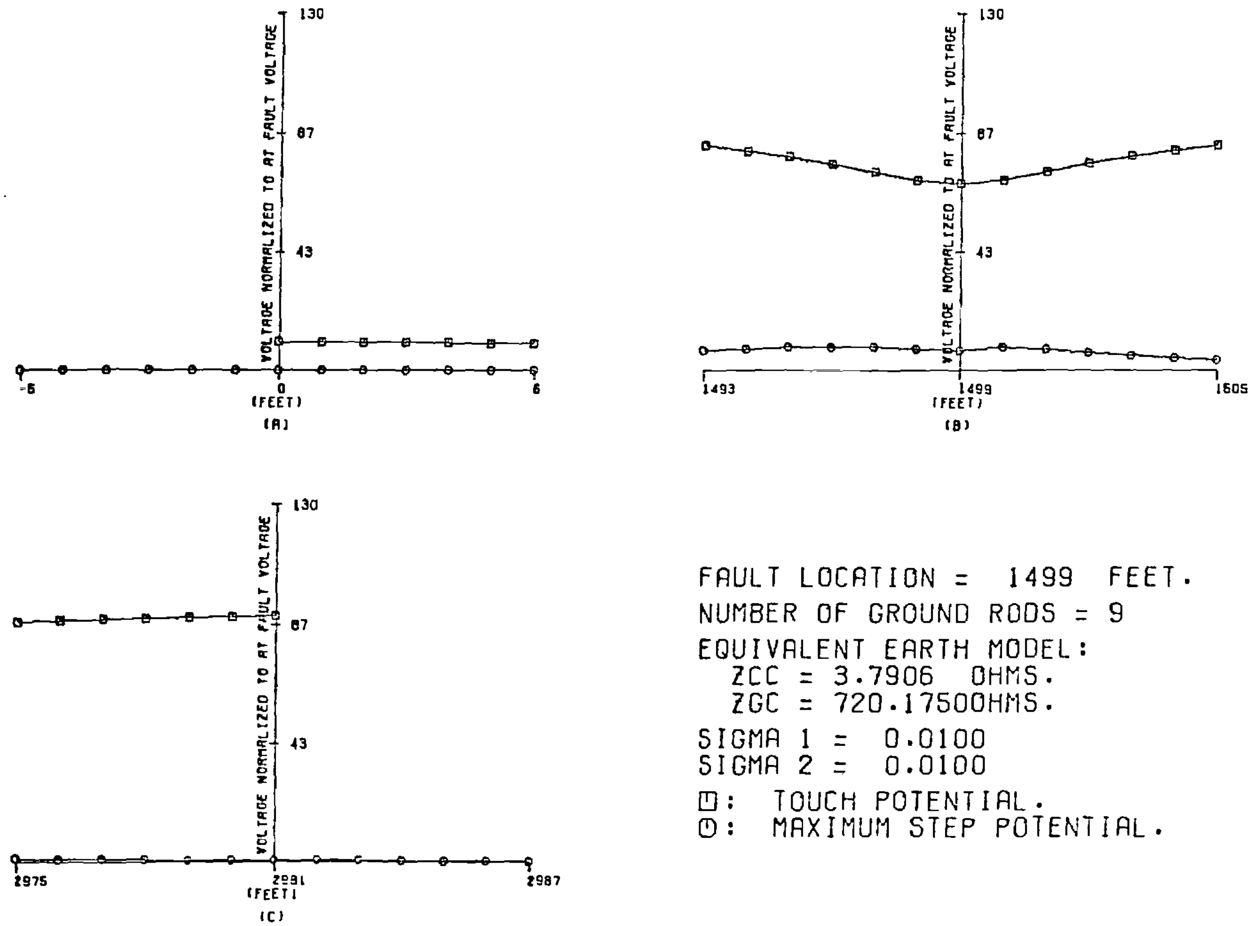
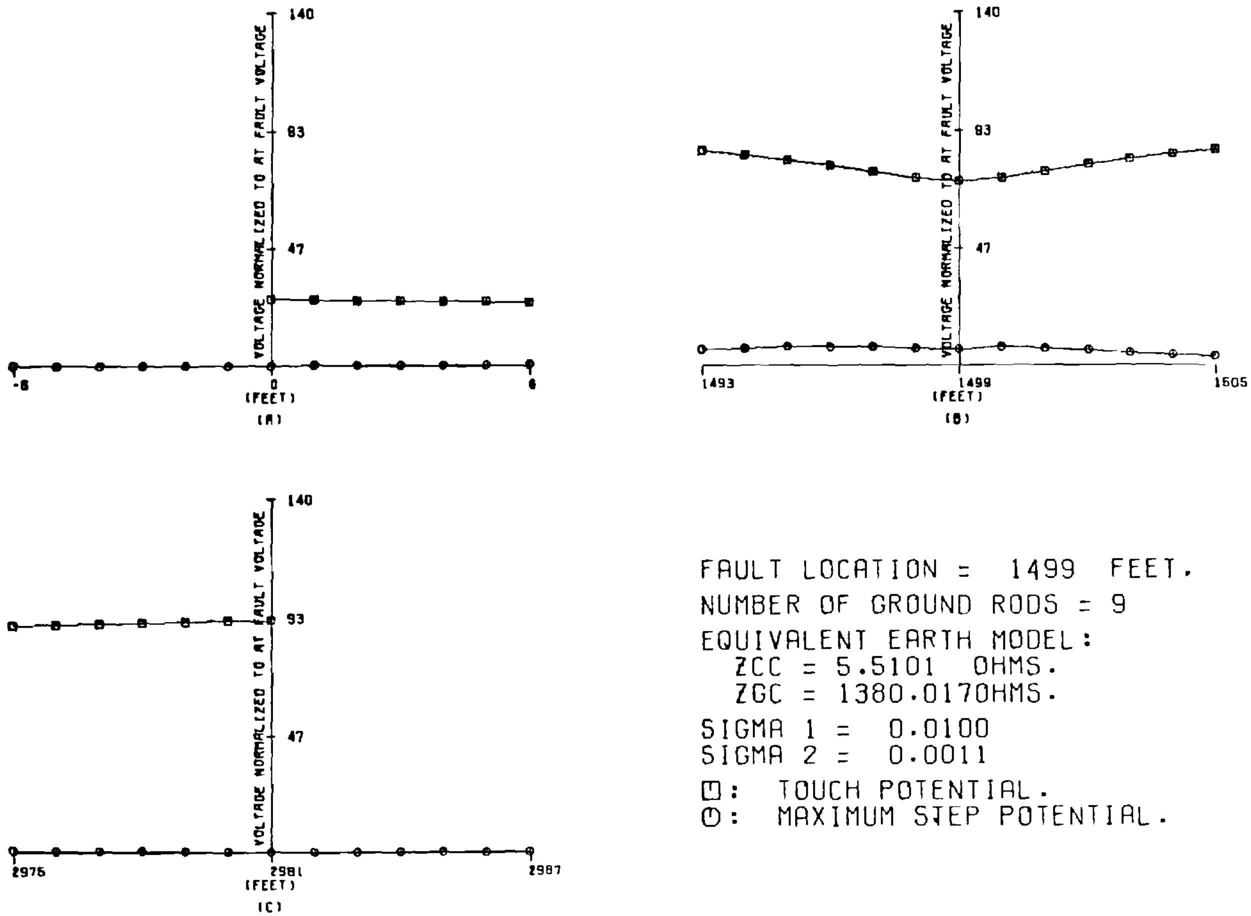


FIGURE A.70. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 5.5101 OHMS.
ZGC = 1380.017OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE A.71. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

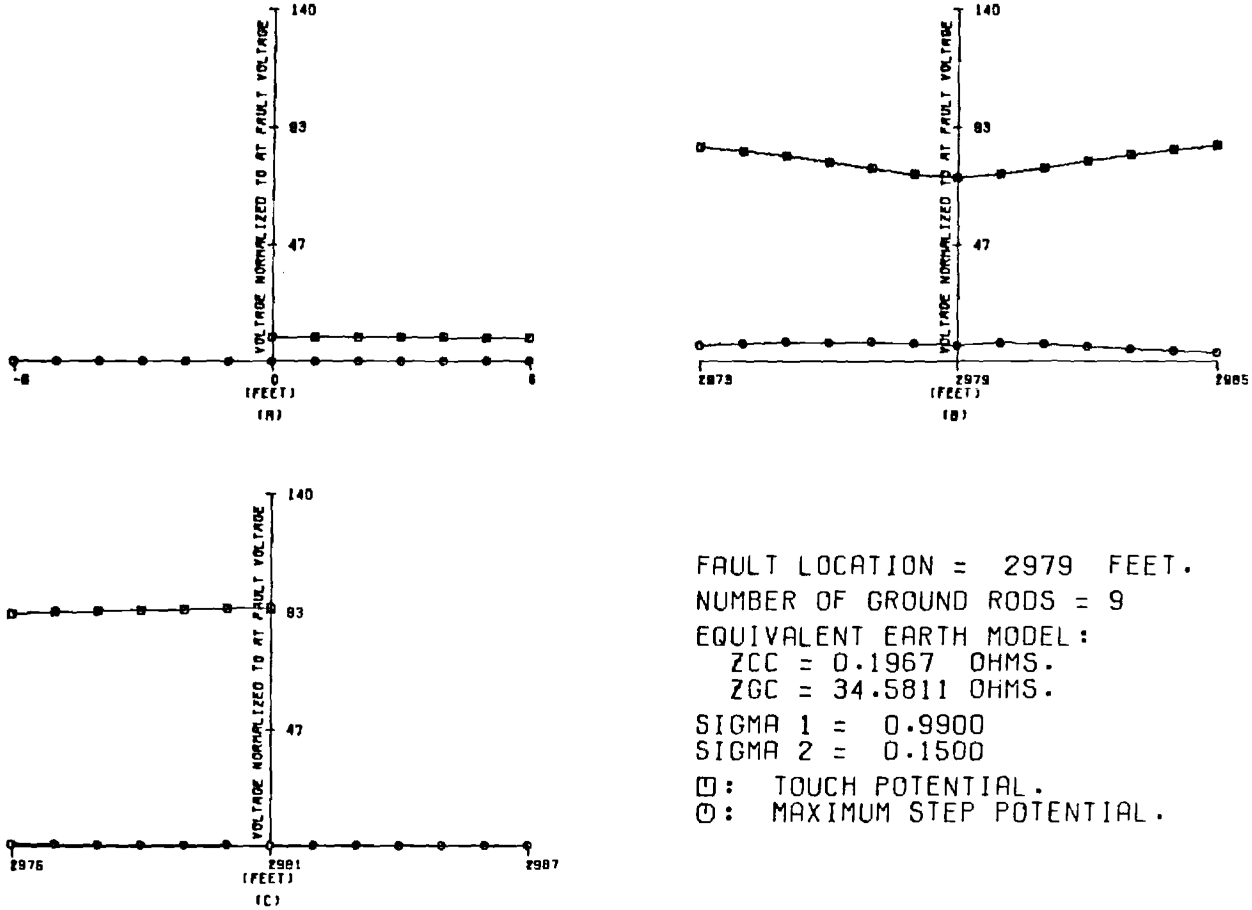


FIGURE A.72. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

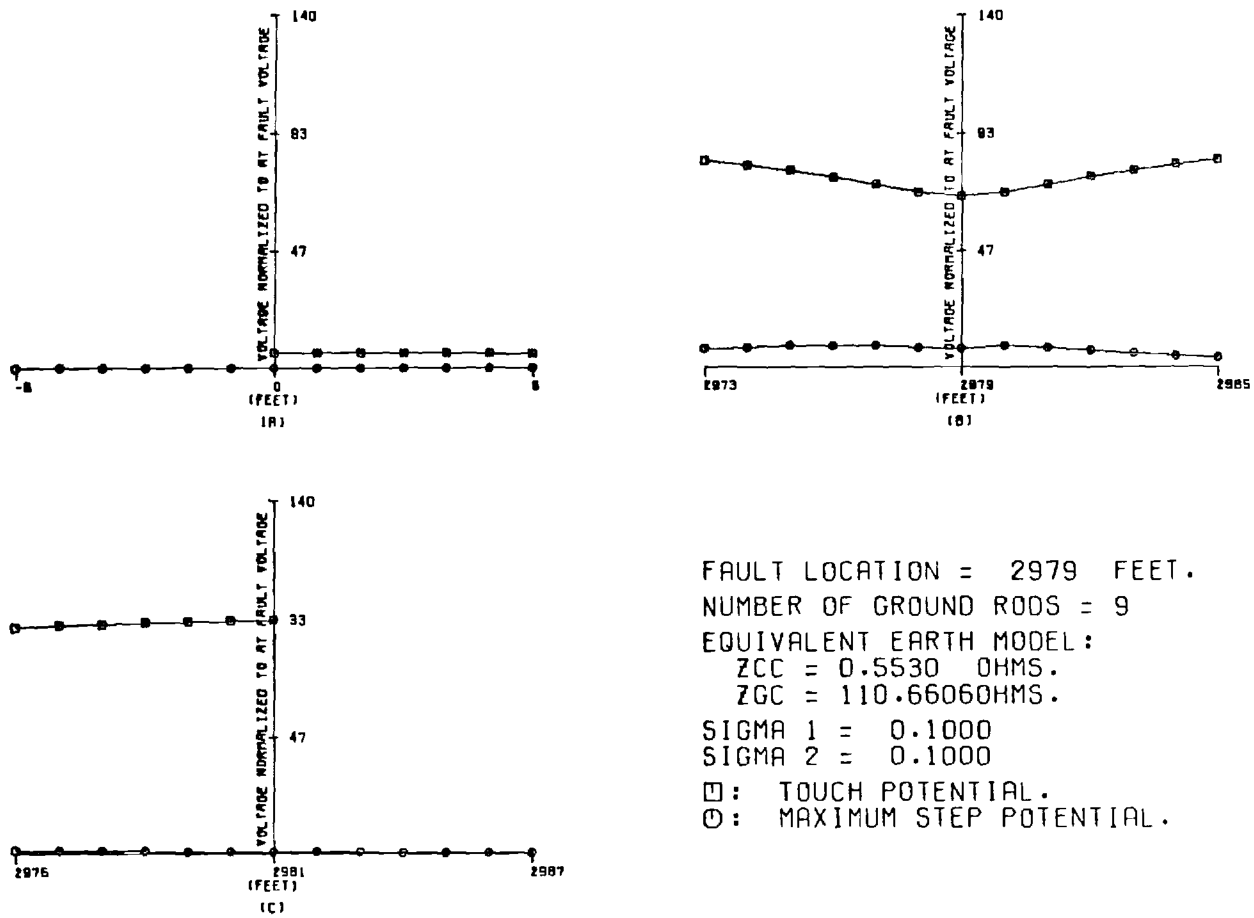


FIGURE A.73. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

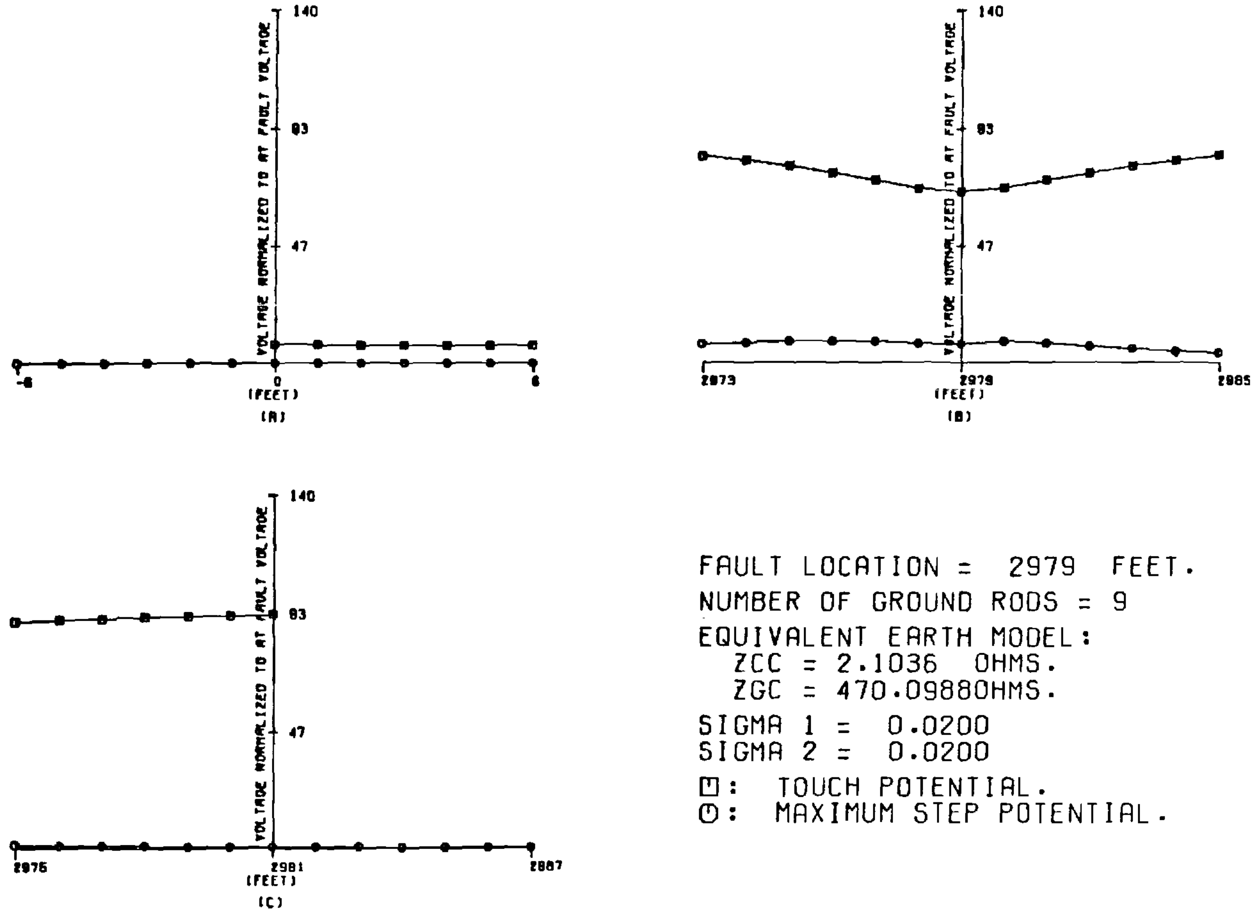


FIGURE A.74. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

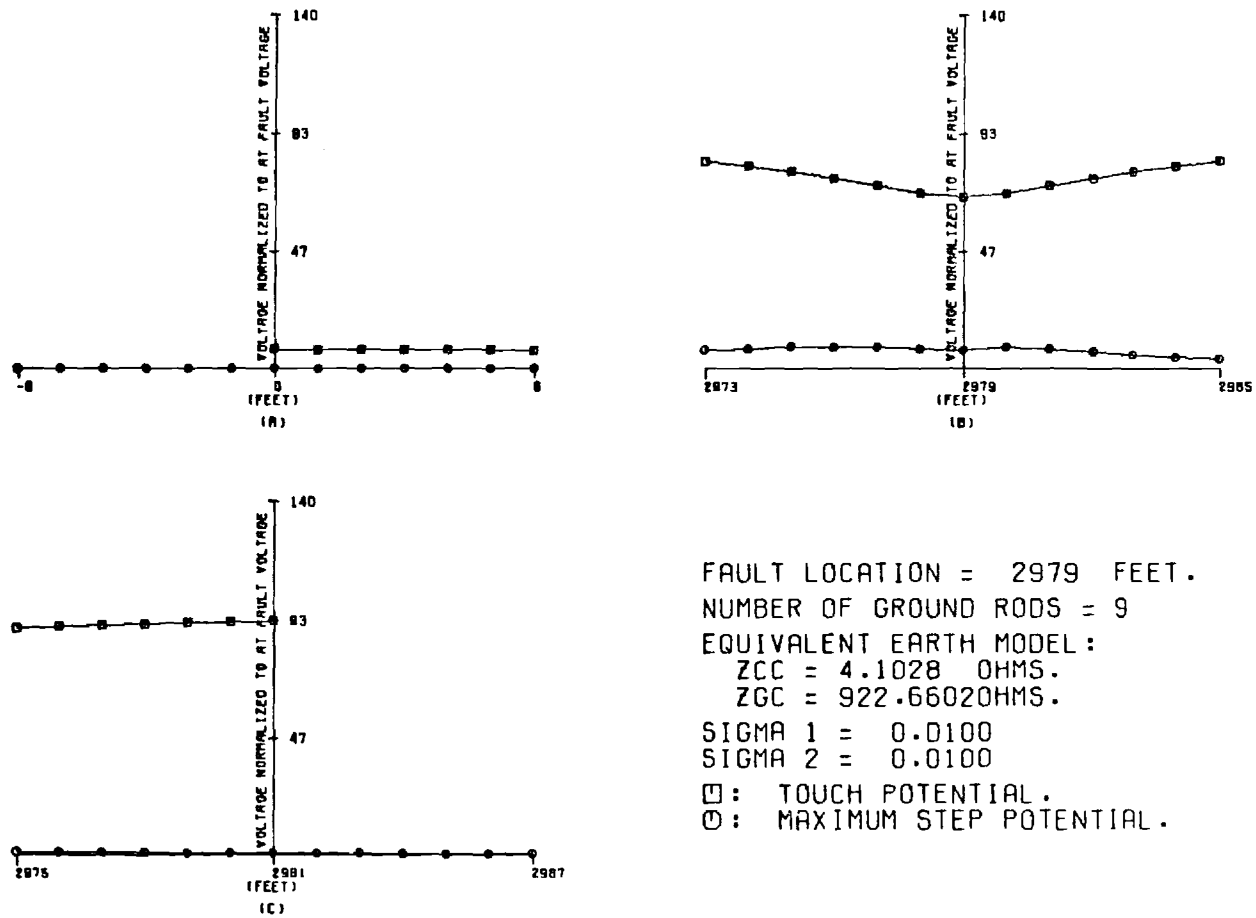
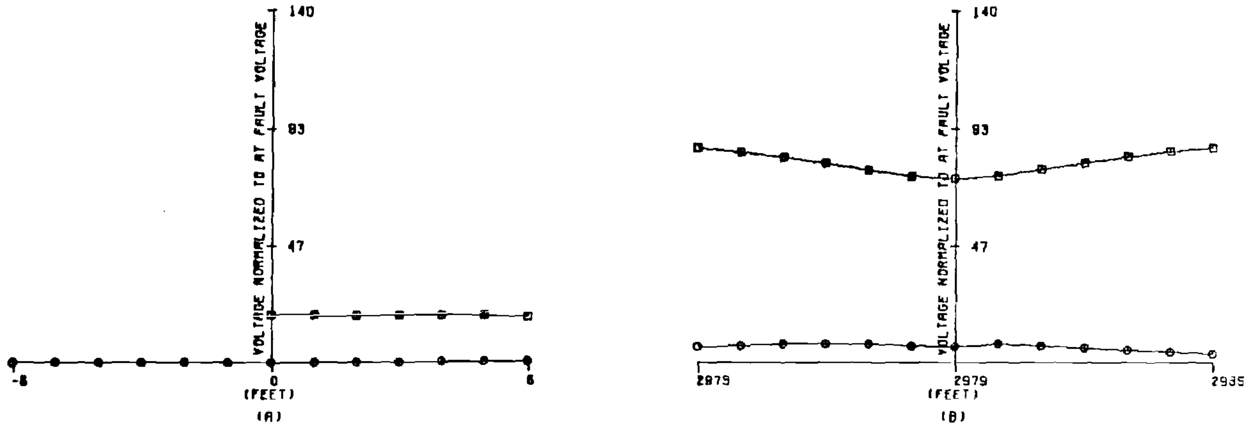
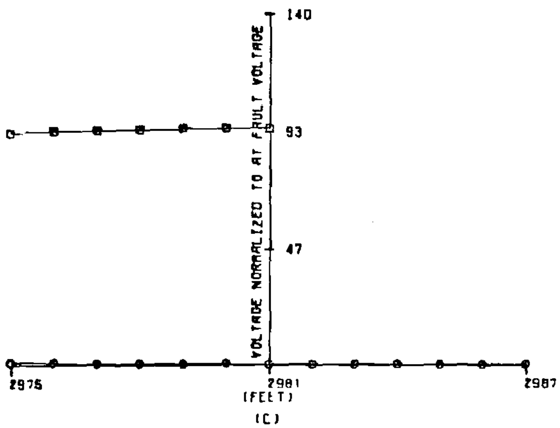


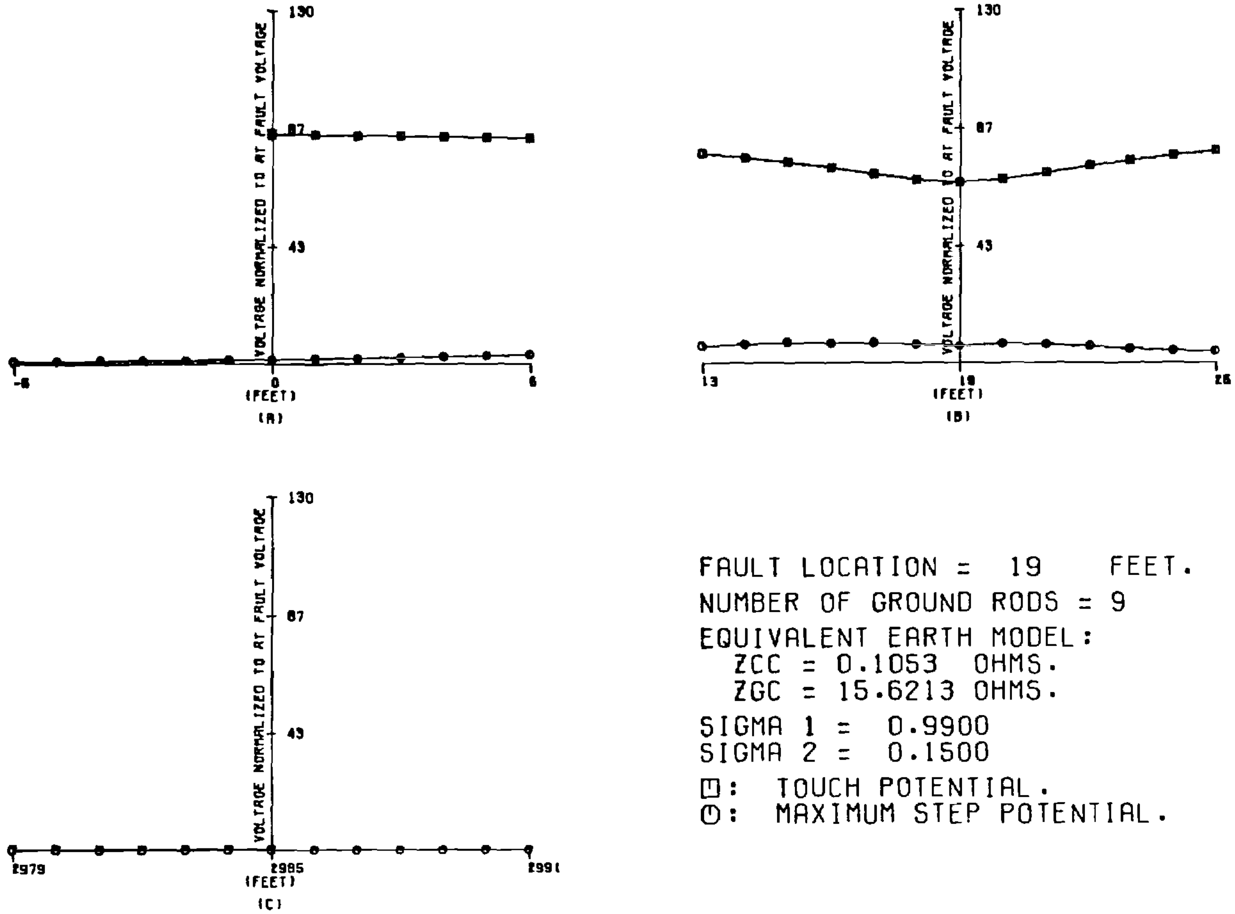
FIGURE A.75. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





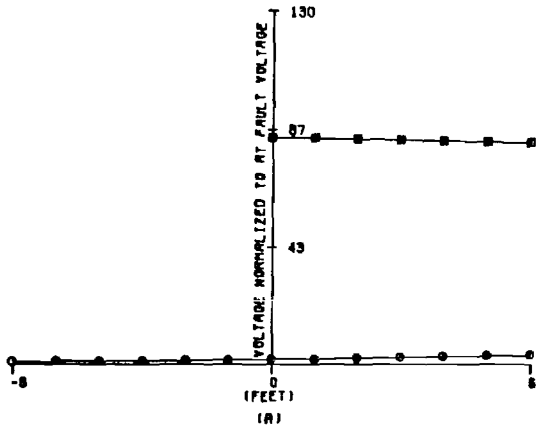
FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 6.2861 OHMS.
ZGC = 1794.582OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

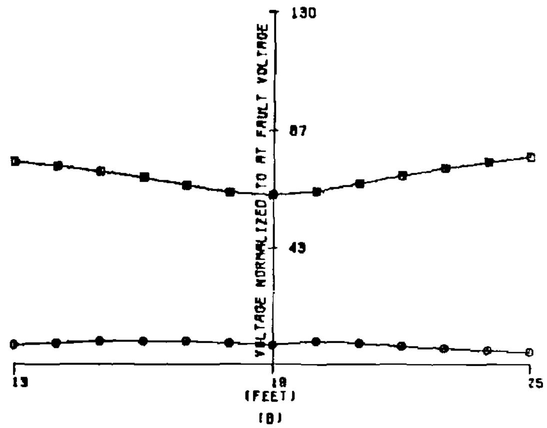
FIGURE A.76. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR [illegible].
C) NEAR [illegible] END.

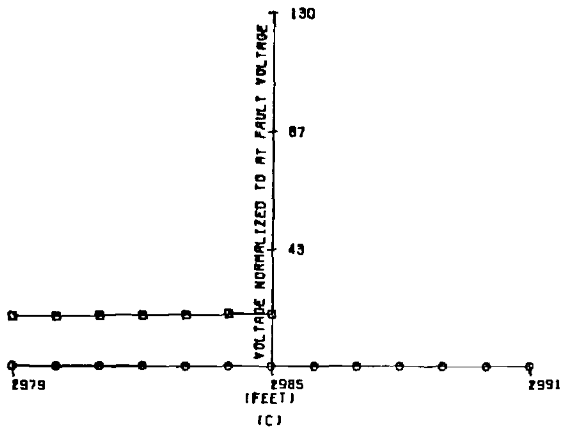


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1053 OHMS.
ZGC = 15.6213 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.77. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.3922 OHMS.
ZGC = 49.0362 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.78. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

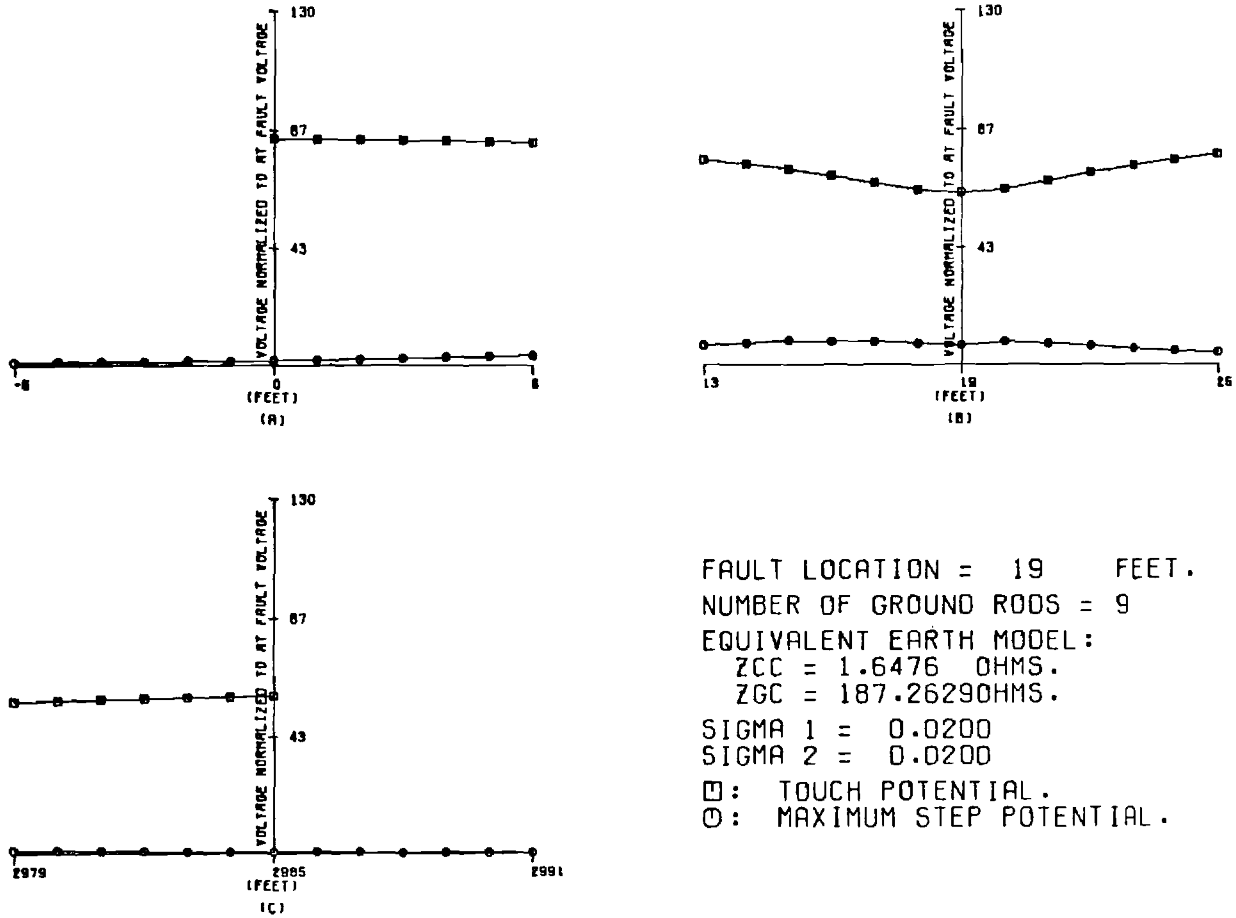
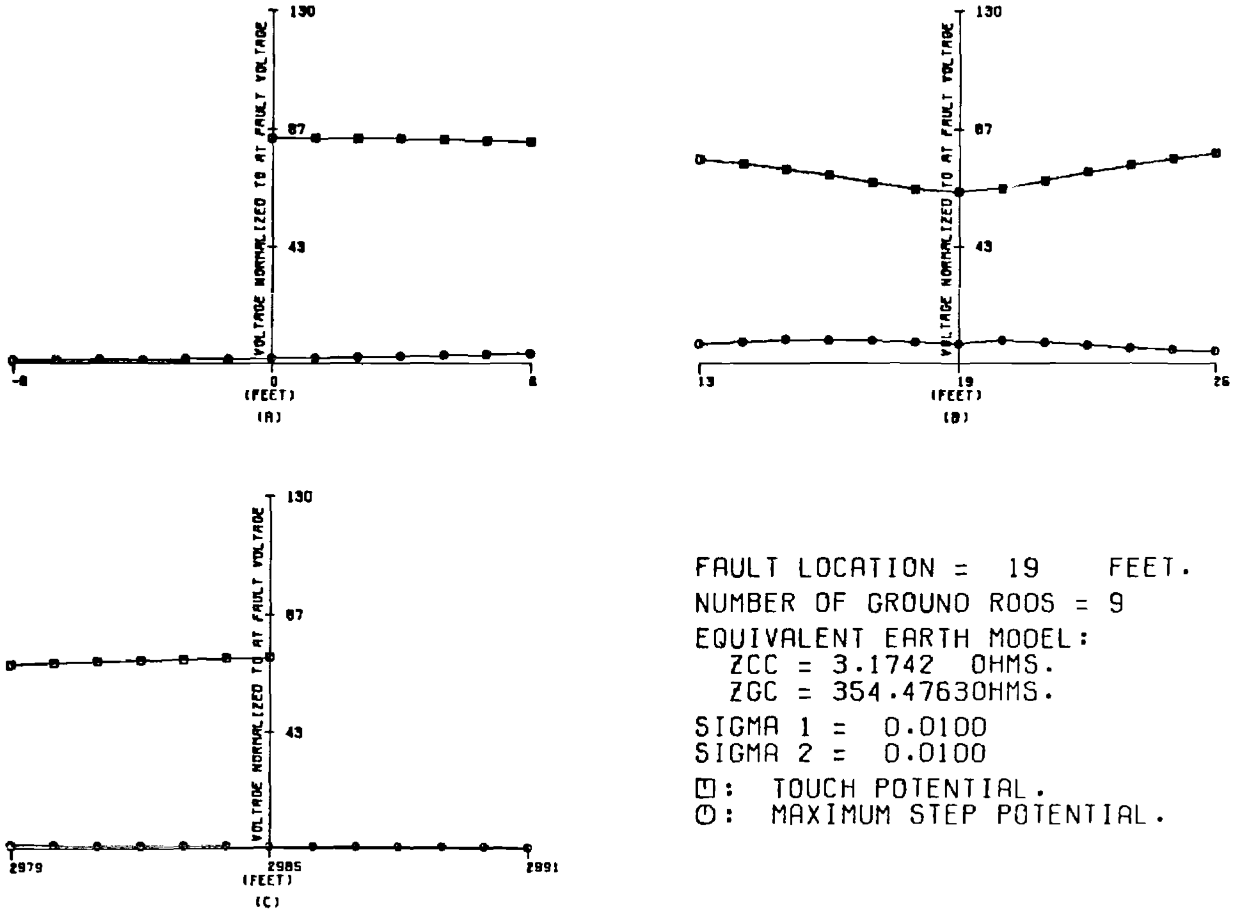


FIGURE A.79. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 3.1742 OHMS.
ZGC = 354.4763OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.80. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

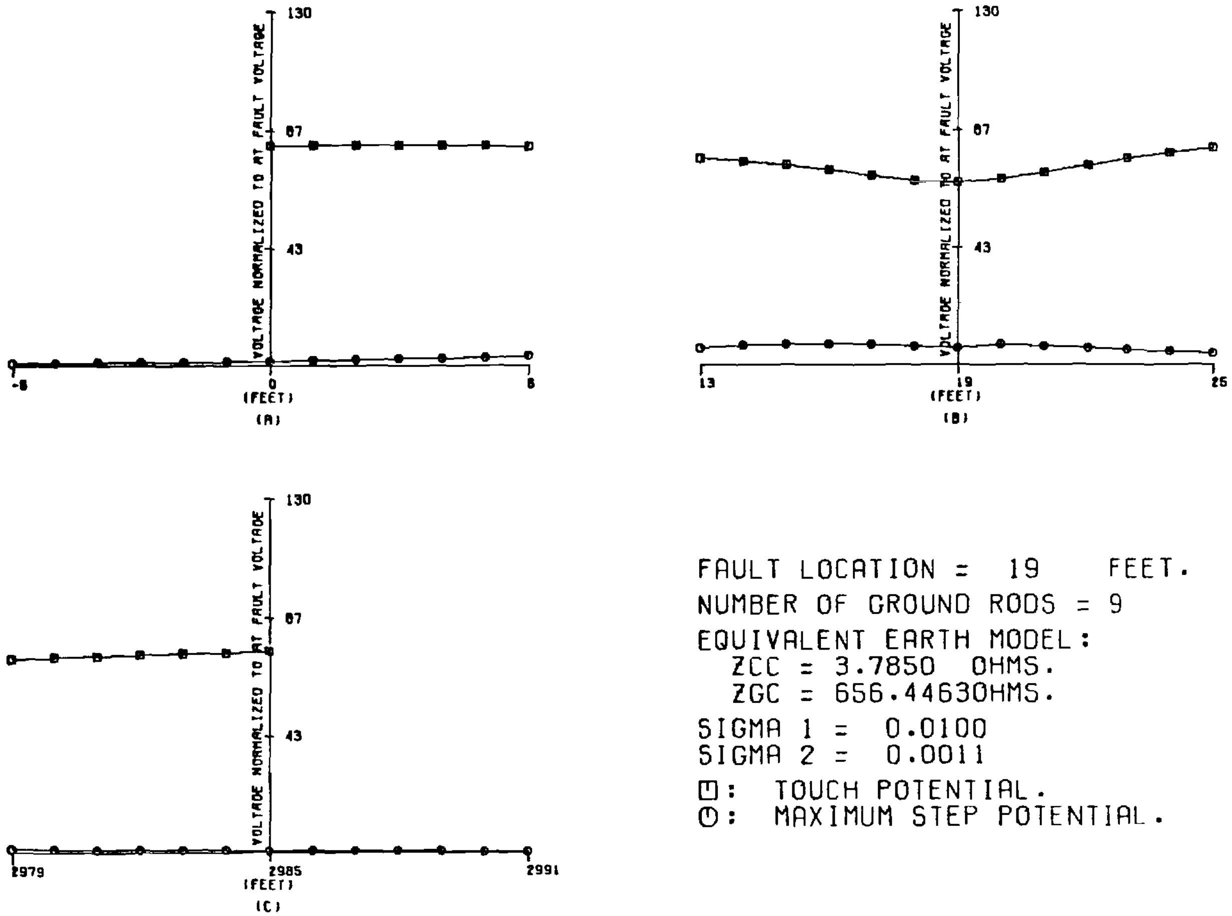
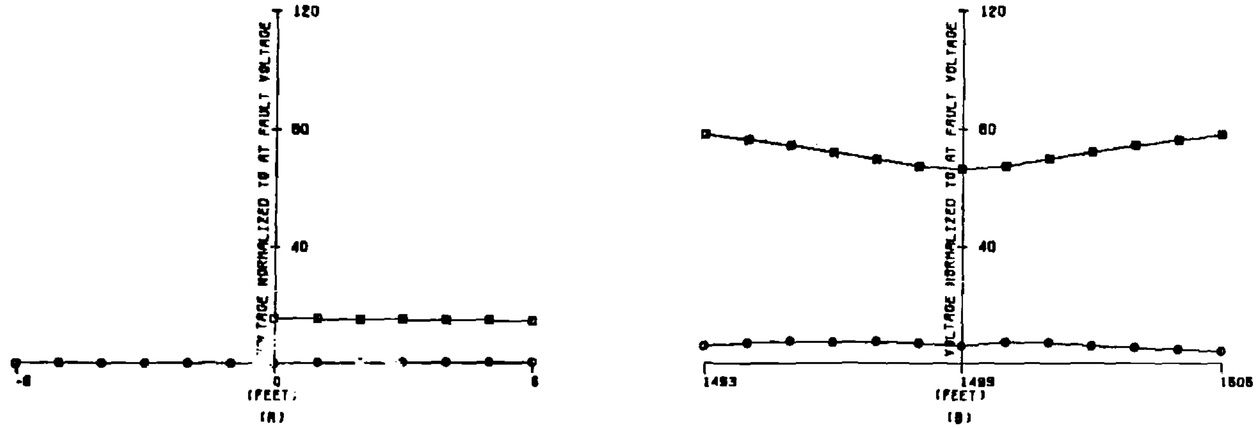
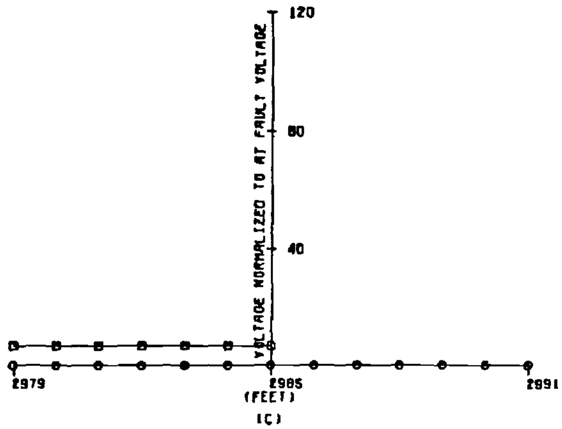


FIGURE A.81. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.0970 OHMS.
ZGC = 13.8960 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
▢: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.82. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

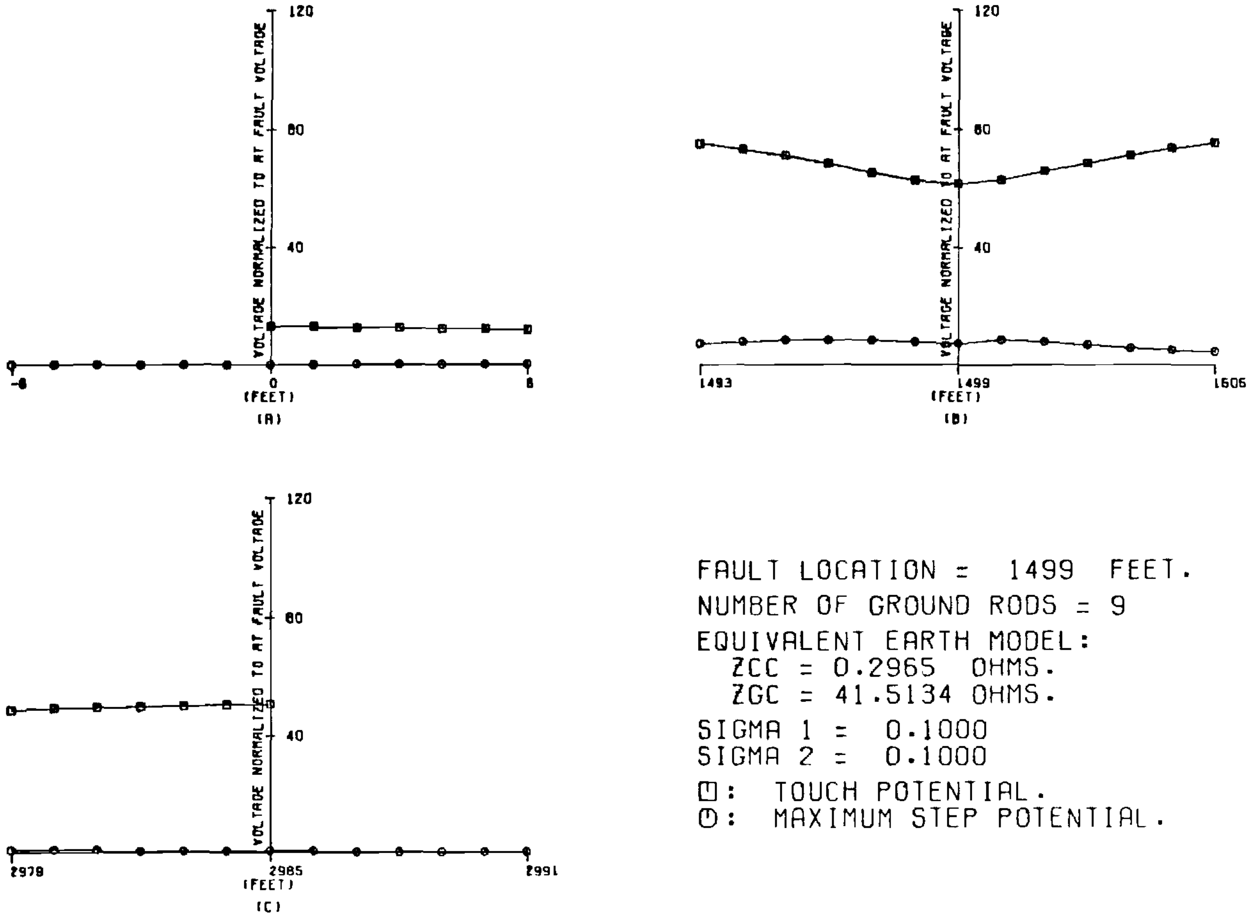


FIGURE A.83. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

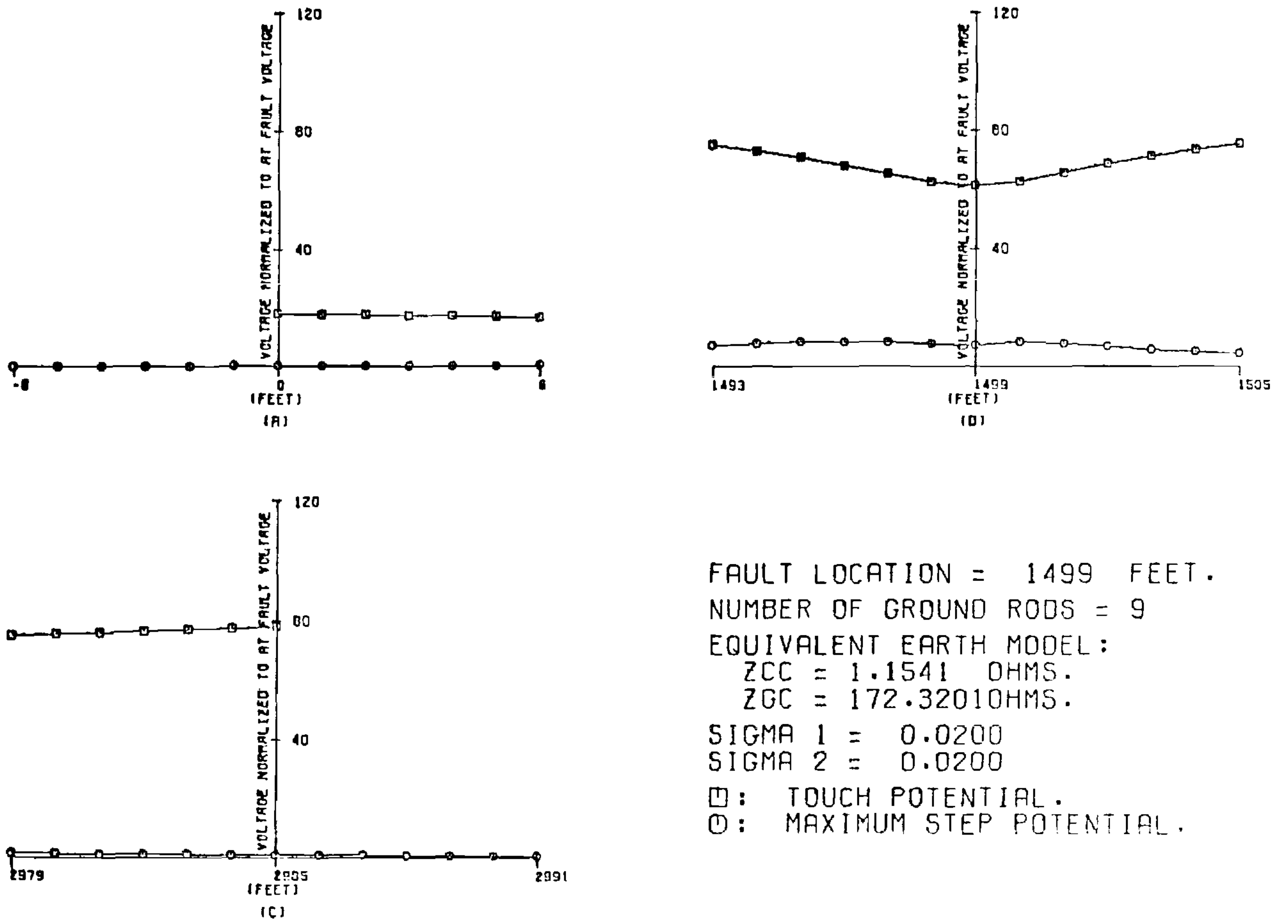


FIGURE A.84. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

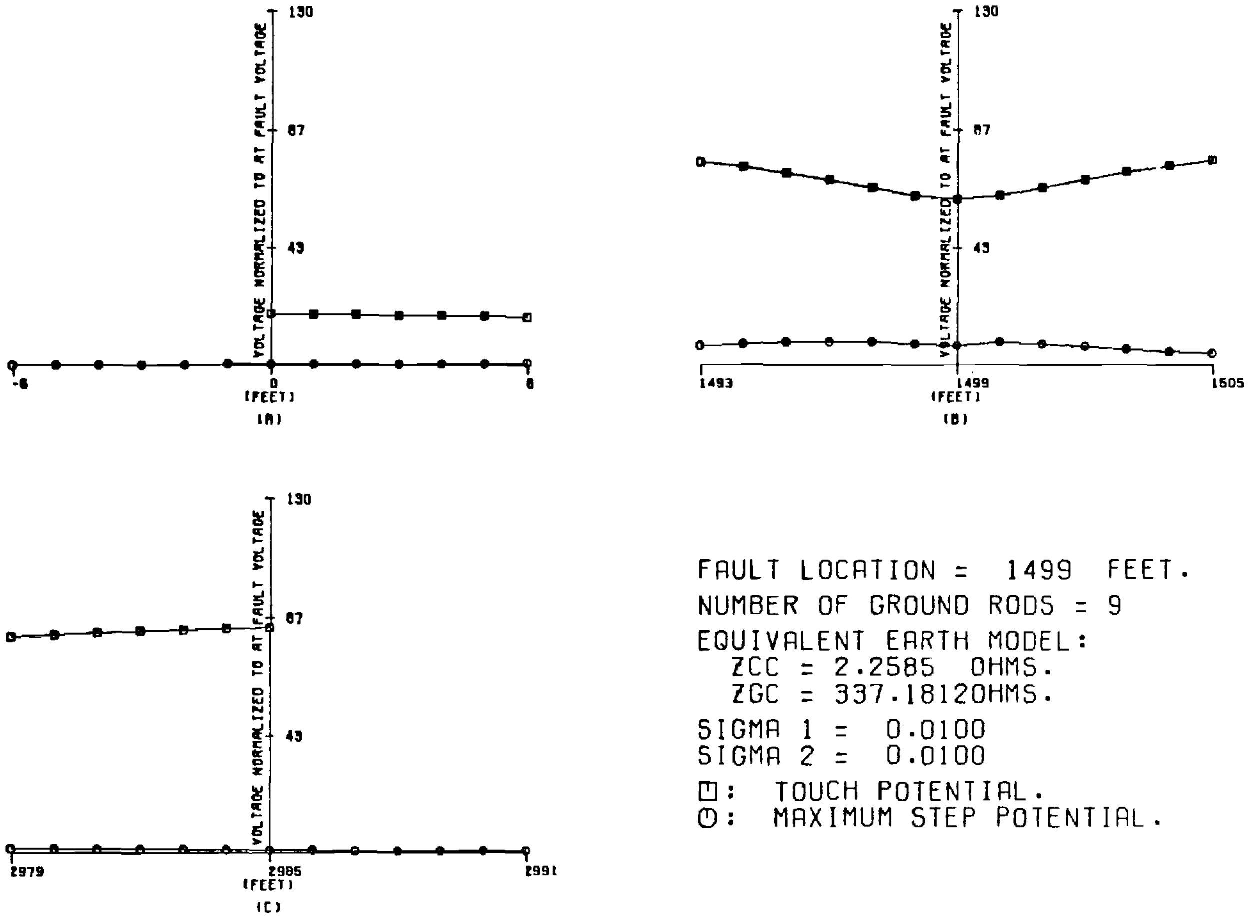
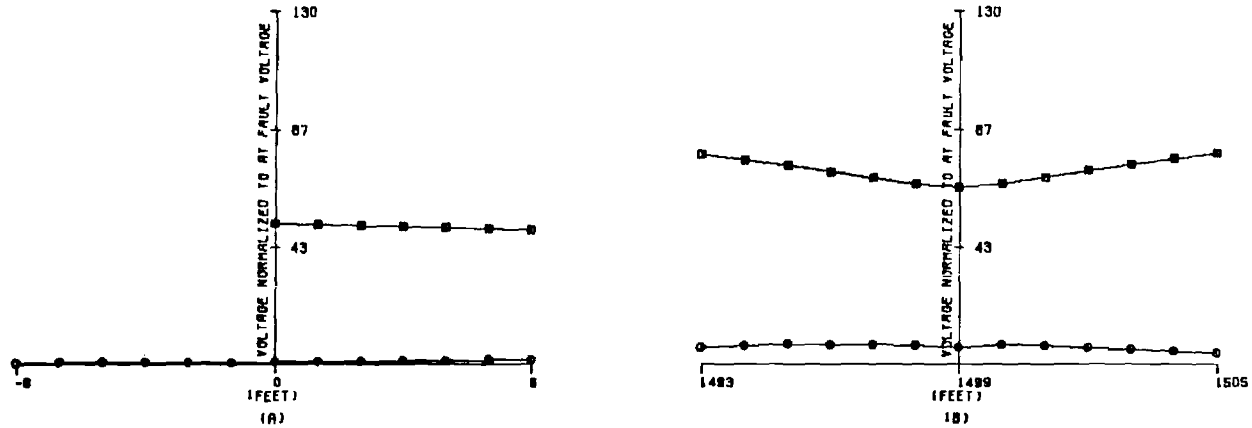
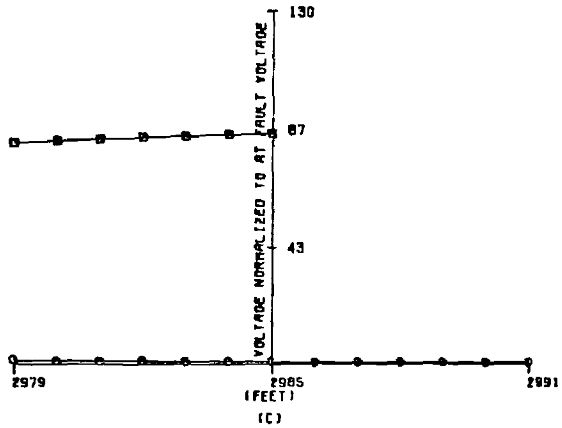


FIGURE A.85. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 3.1200 OHMS.
ZGC = 672.2006OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.86. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

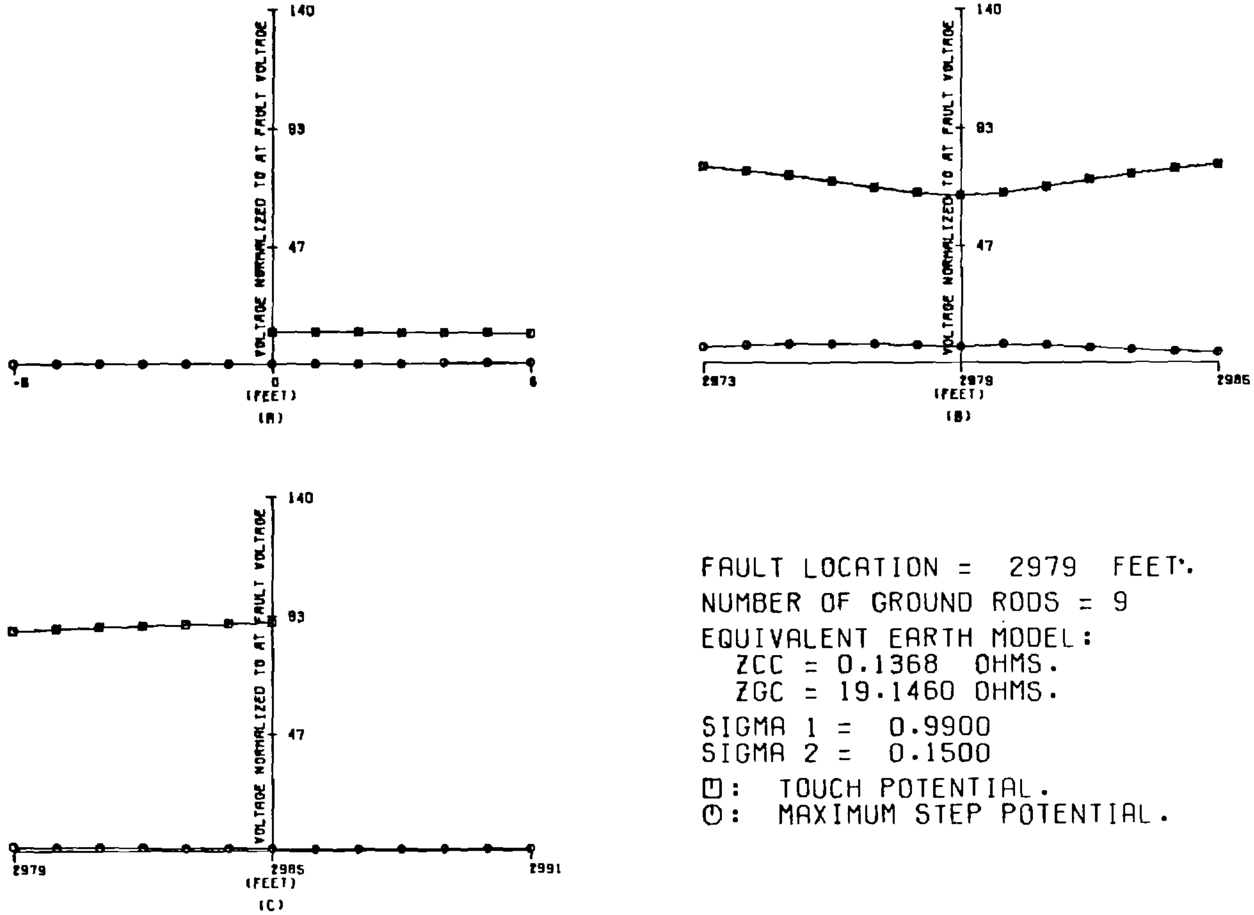
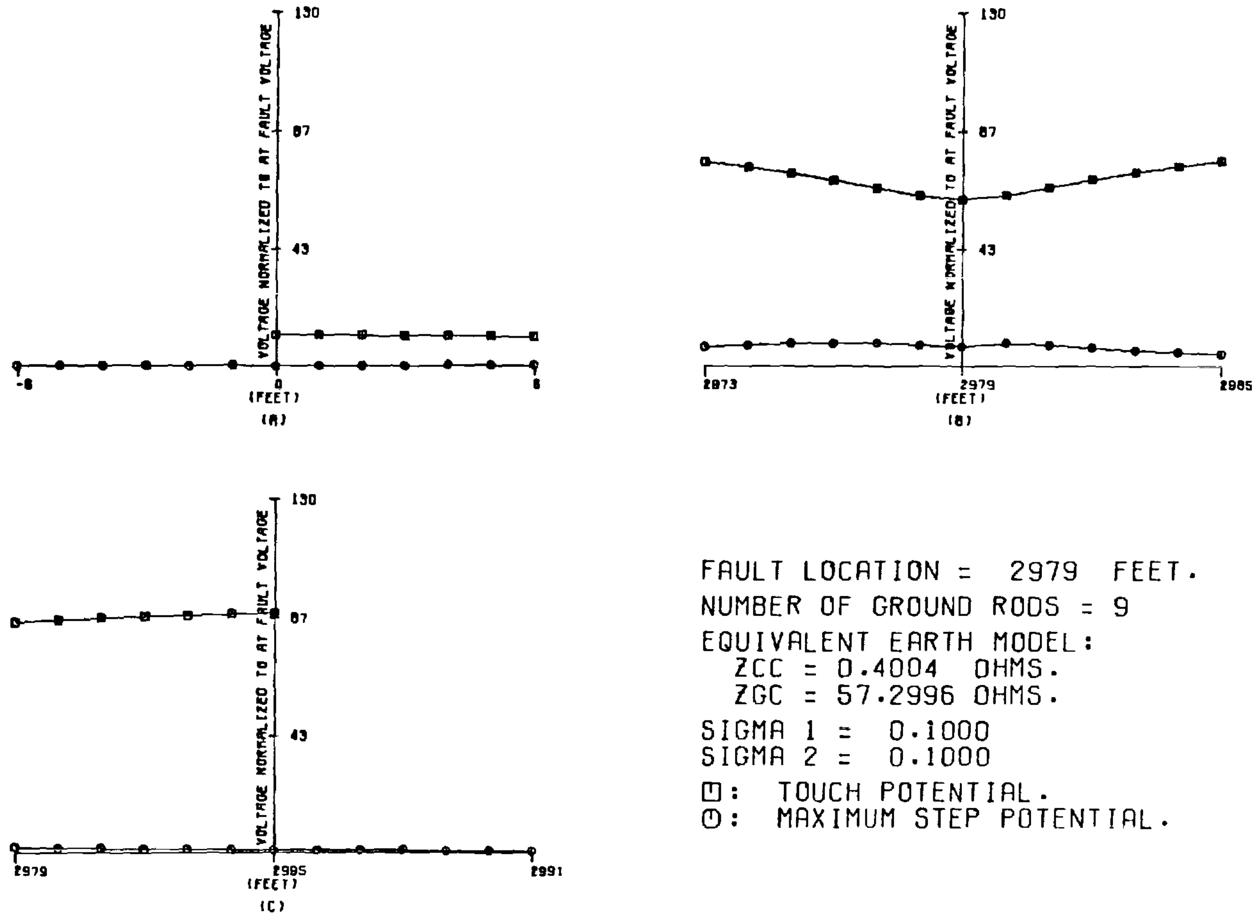


FIGURE A.87. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.4004 OHMS.
ZGC = 57.2996 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.83. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

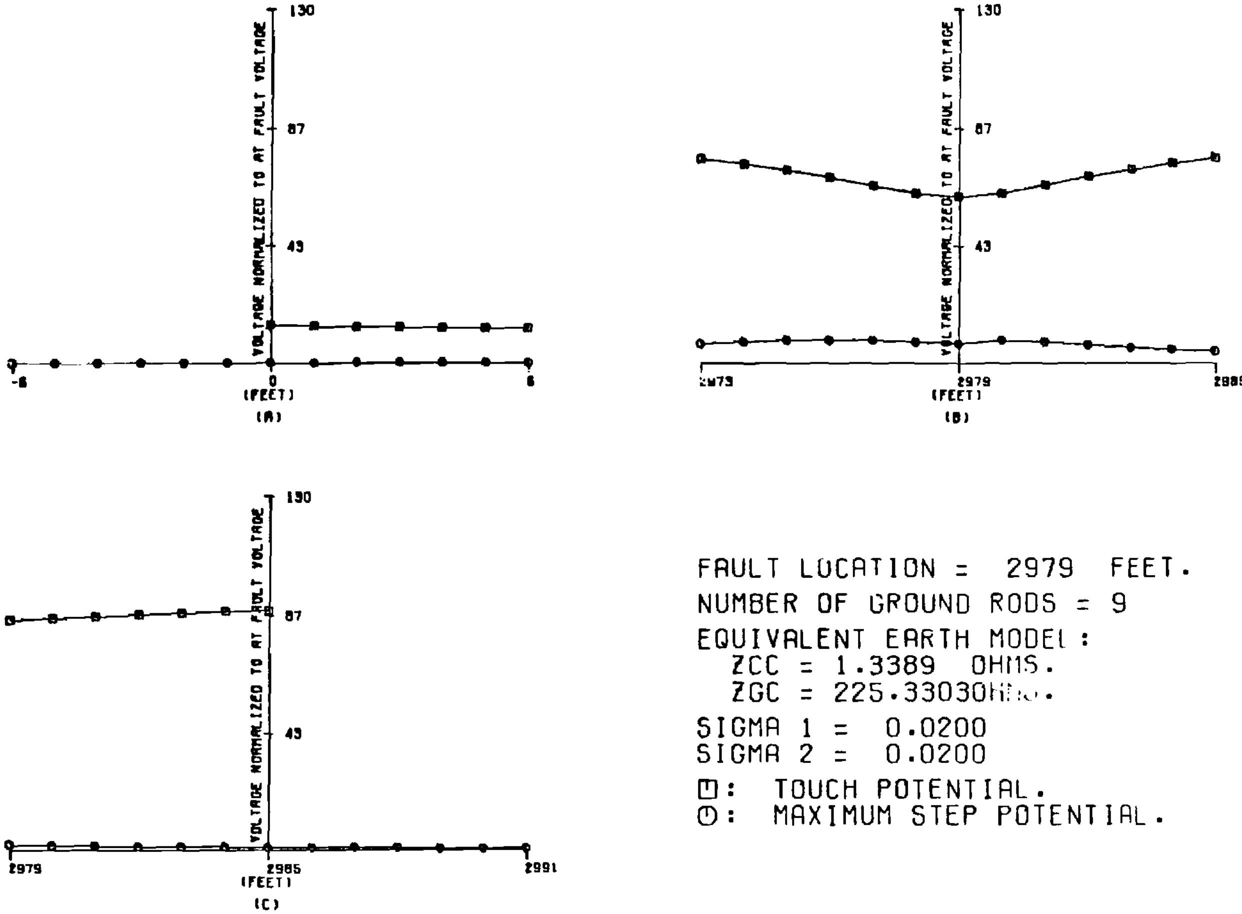


FIGURE A.89. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

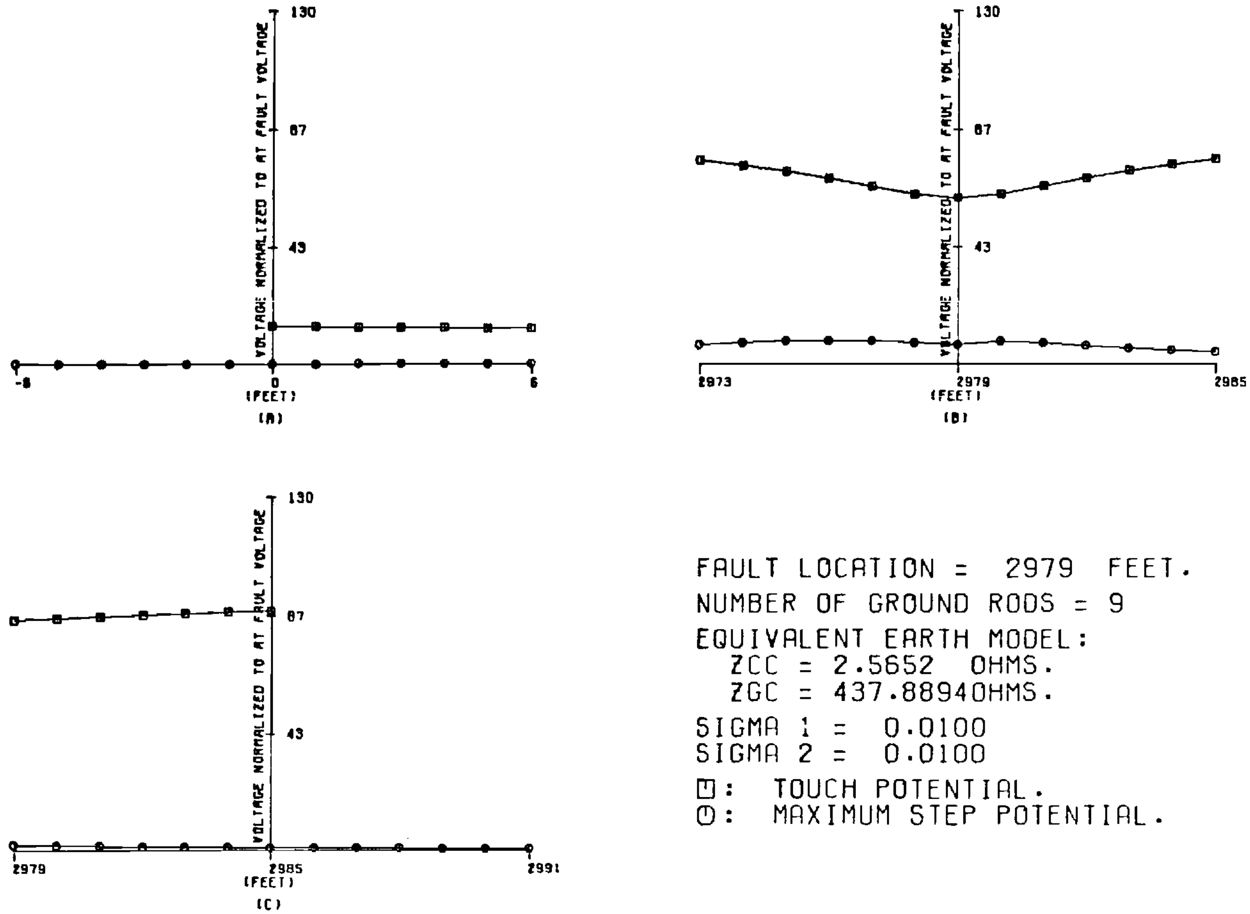


FIGURE A.90. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

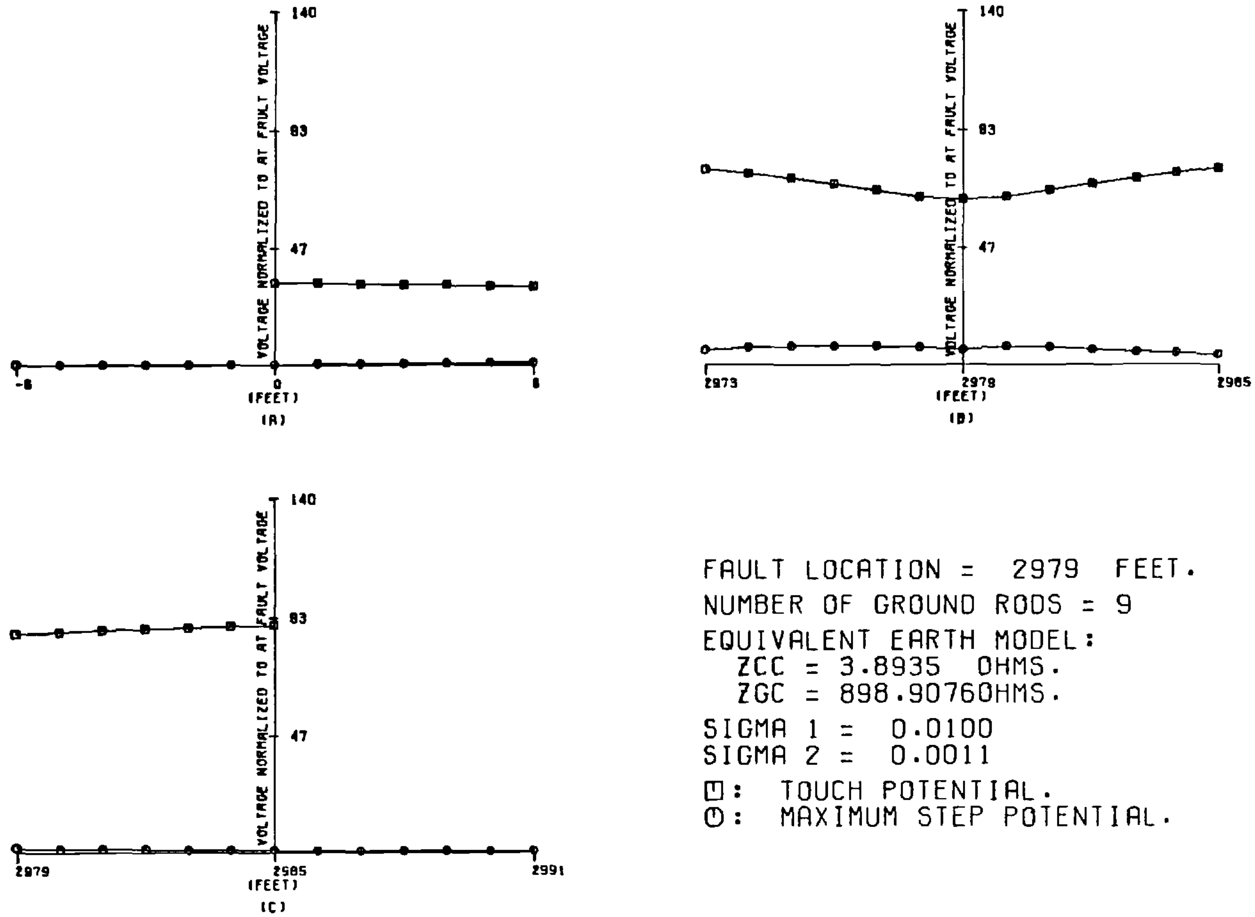


FIGURE A.91. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

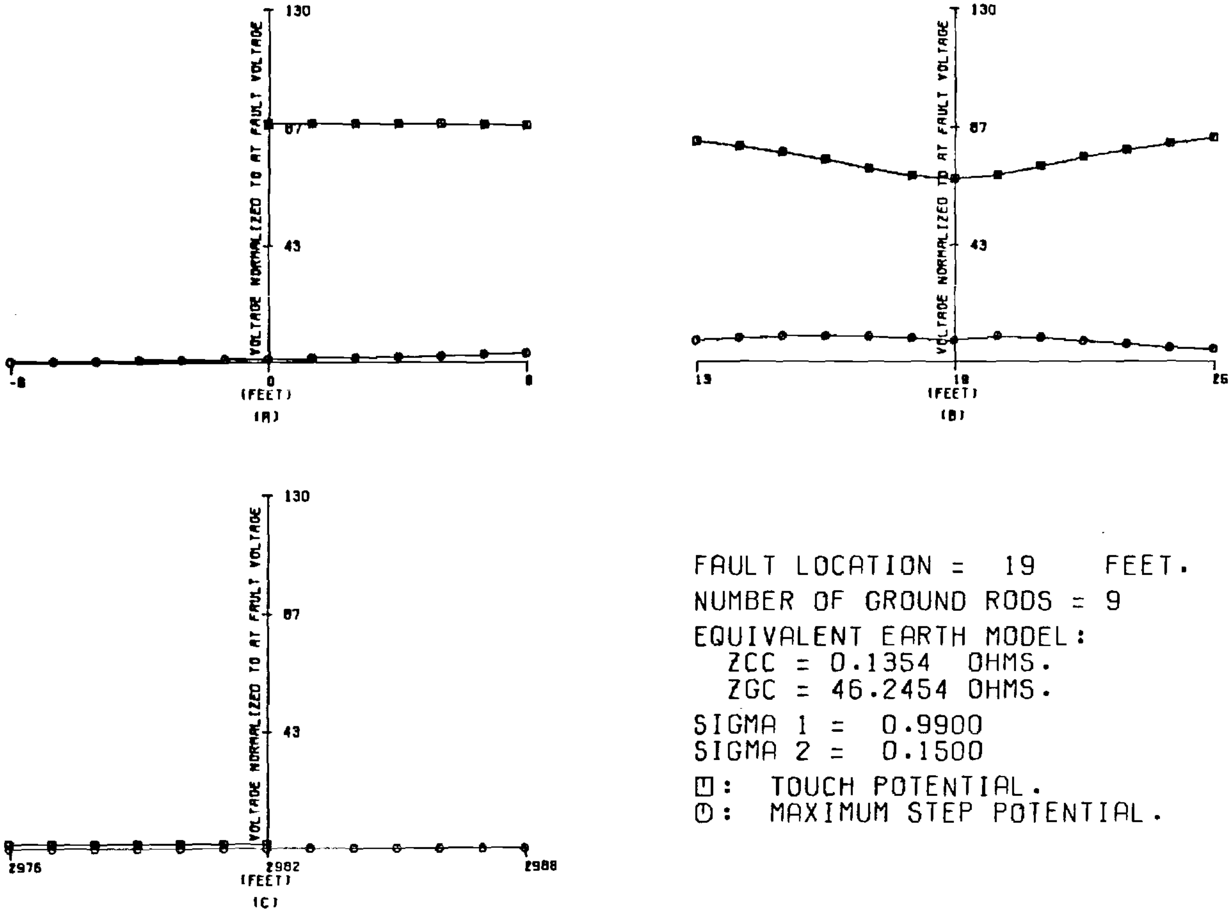


FIGURE A.92. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

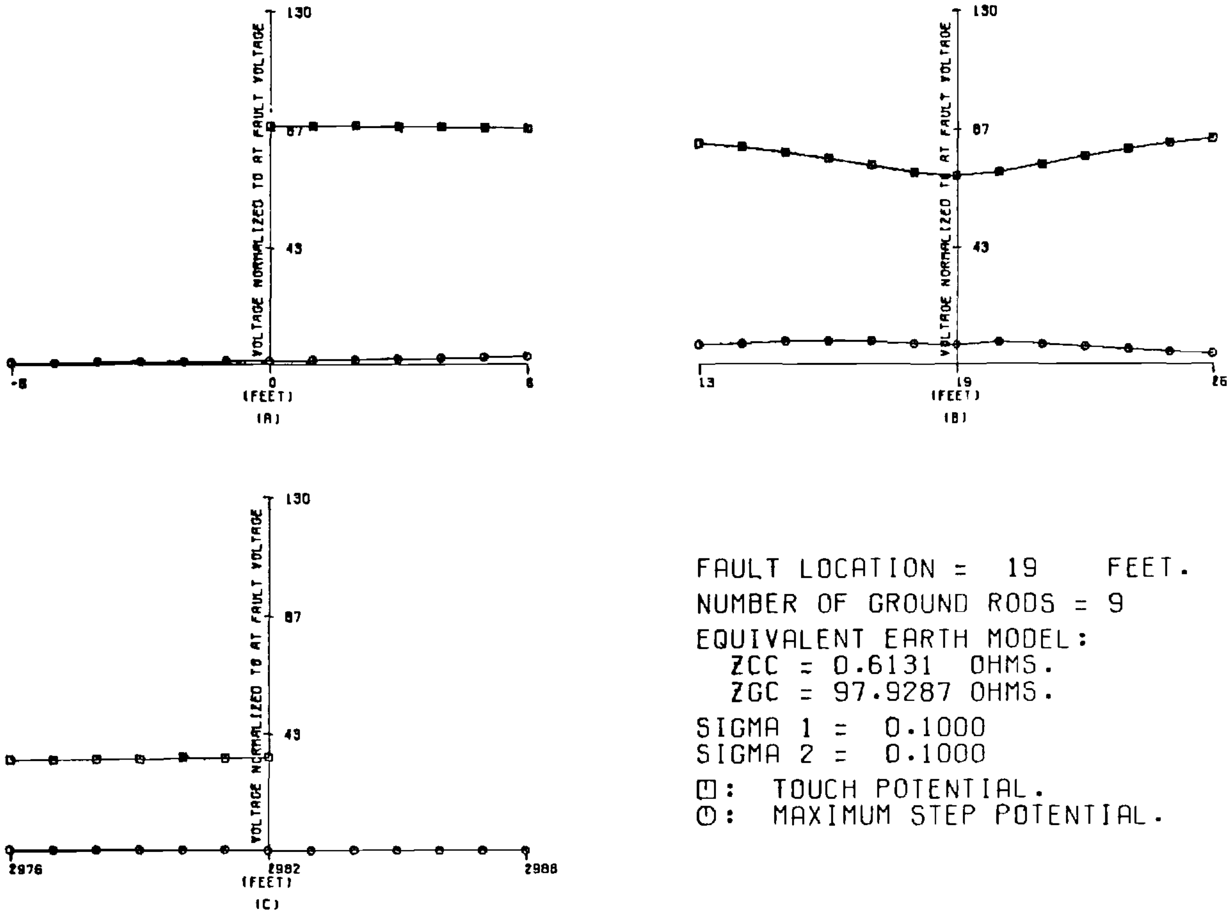


FIGURE A.93. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

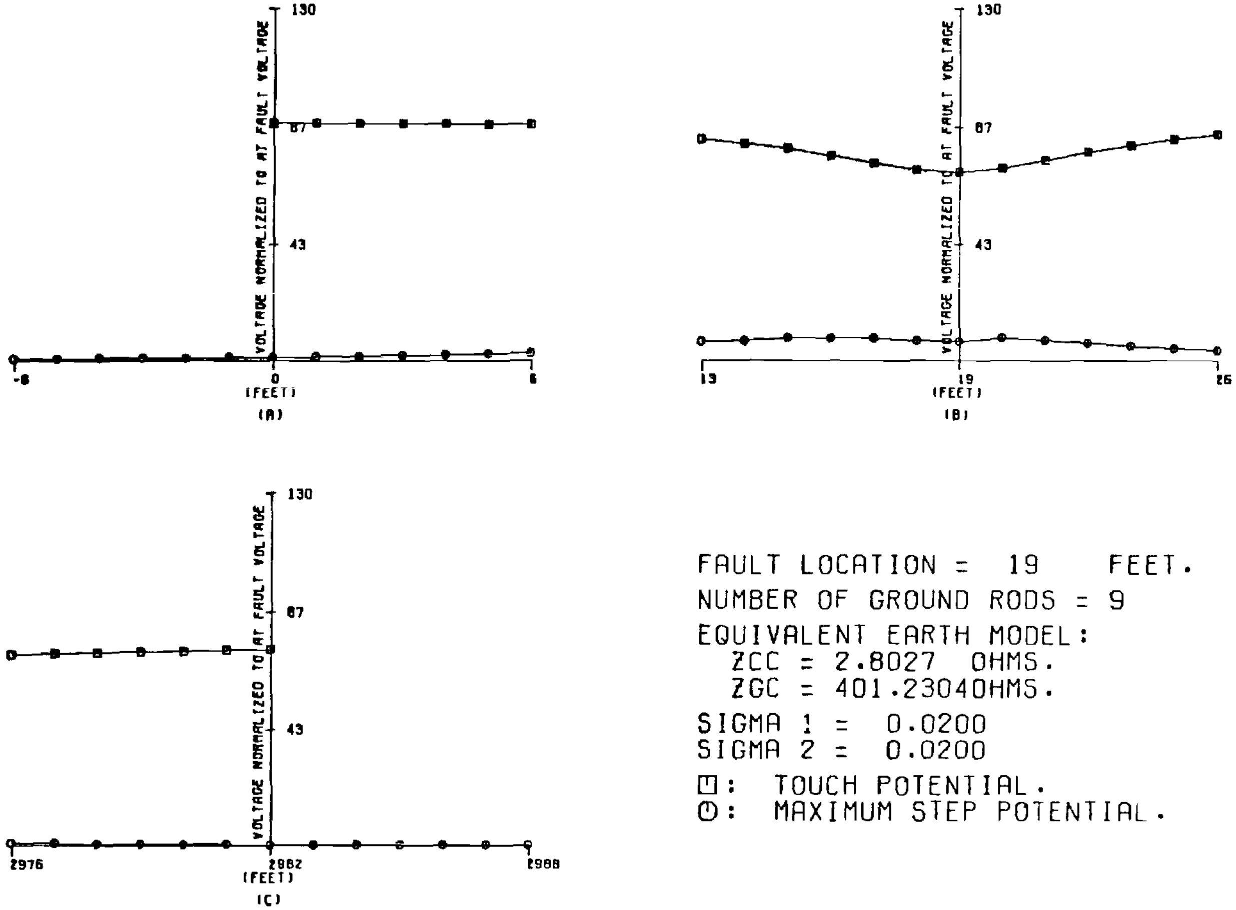
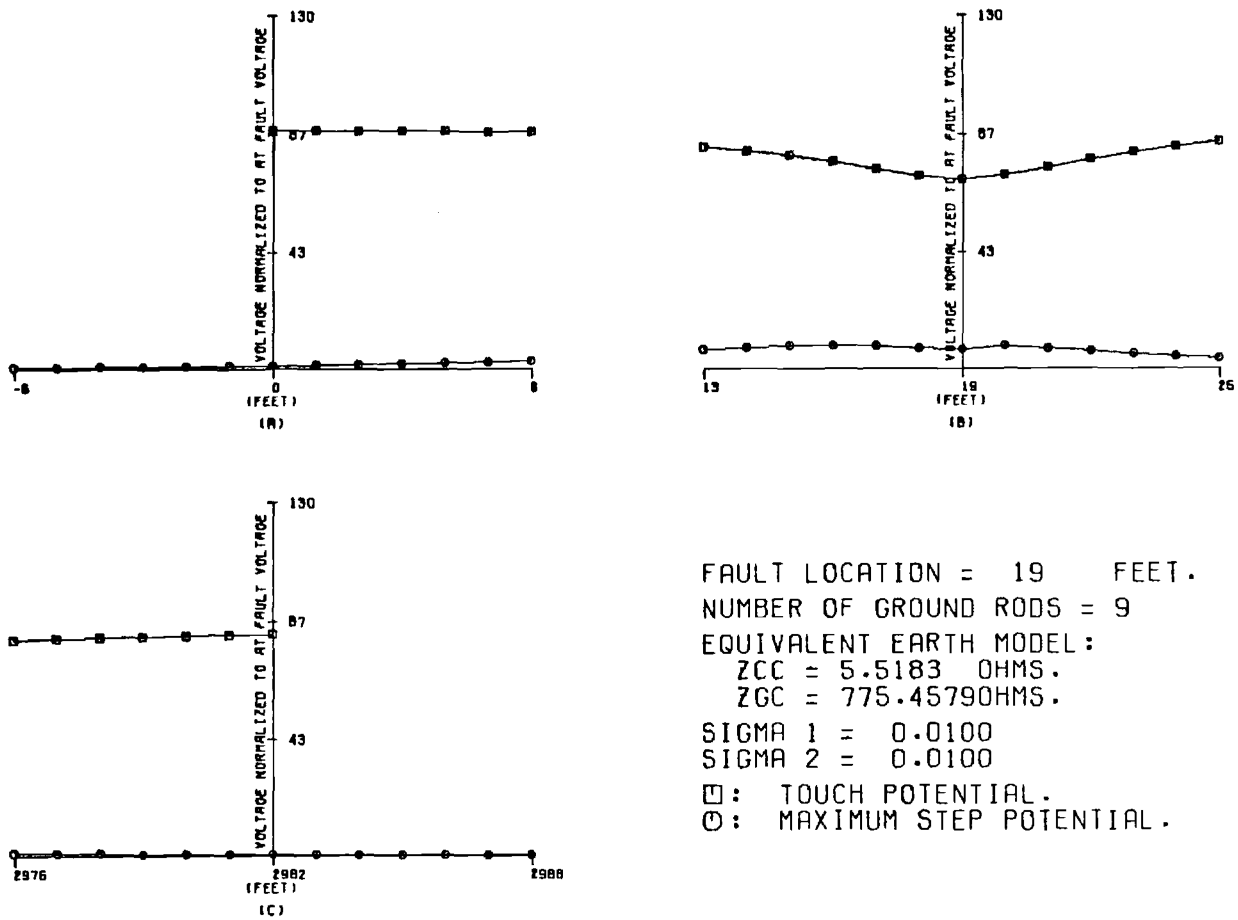
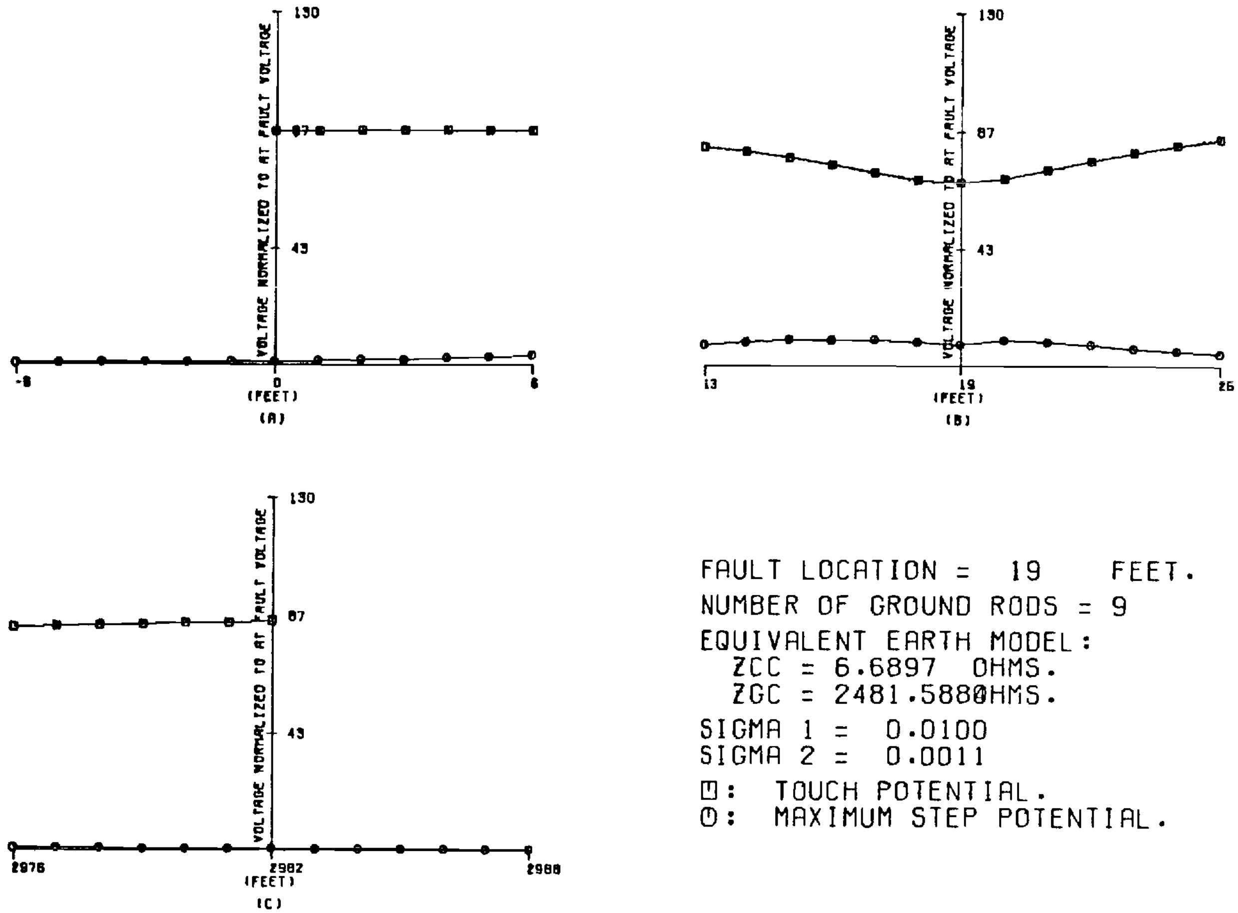


FIGURE A.94. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



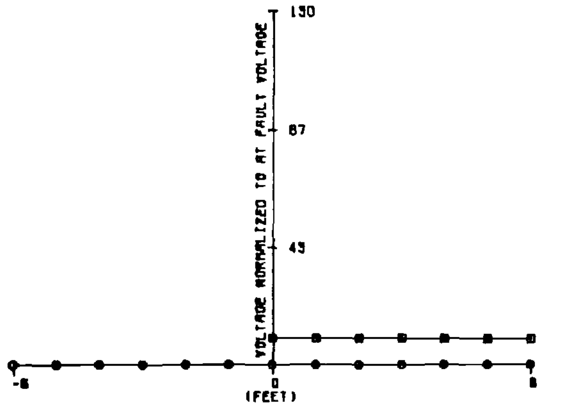
FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 5.5183 OHMS.
ZGC = 775.4579OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.95. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

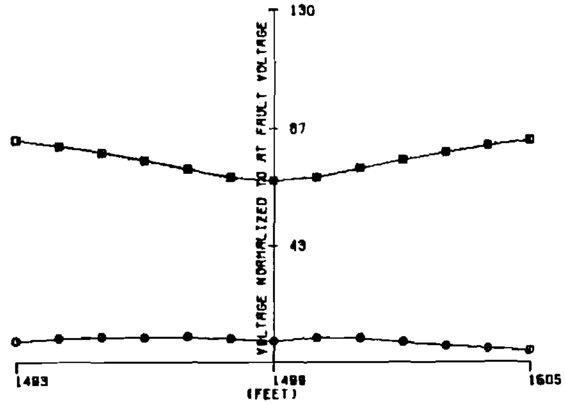


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 6.6897 OHMS.
ZGC = 2481.588OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

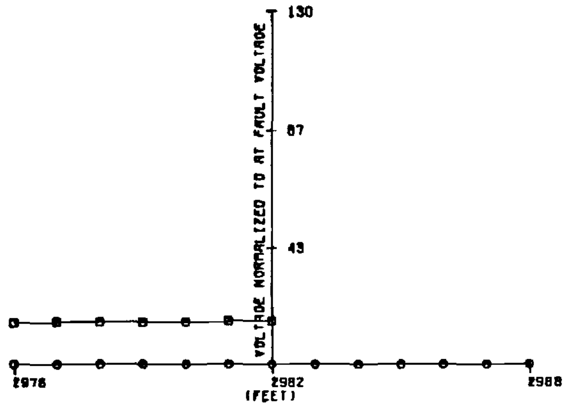
FIGURE A.96. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



(A)



(B)



(C)

FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1261 OHMS.
ZGC = 40.1101 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.97. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

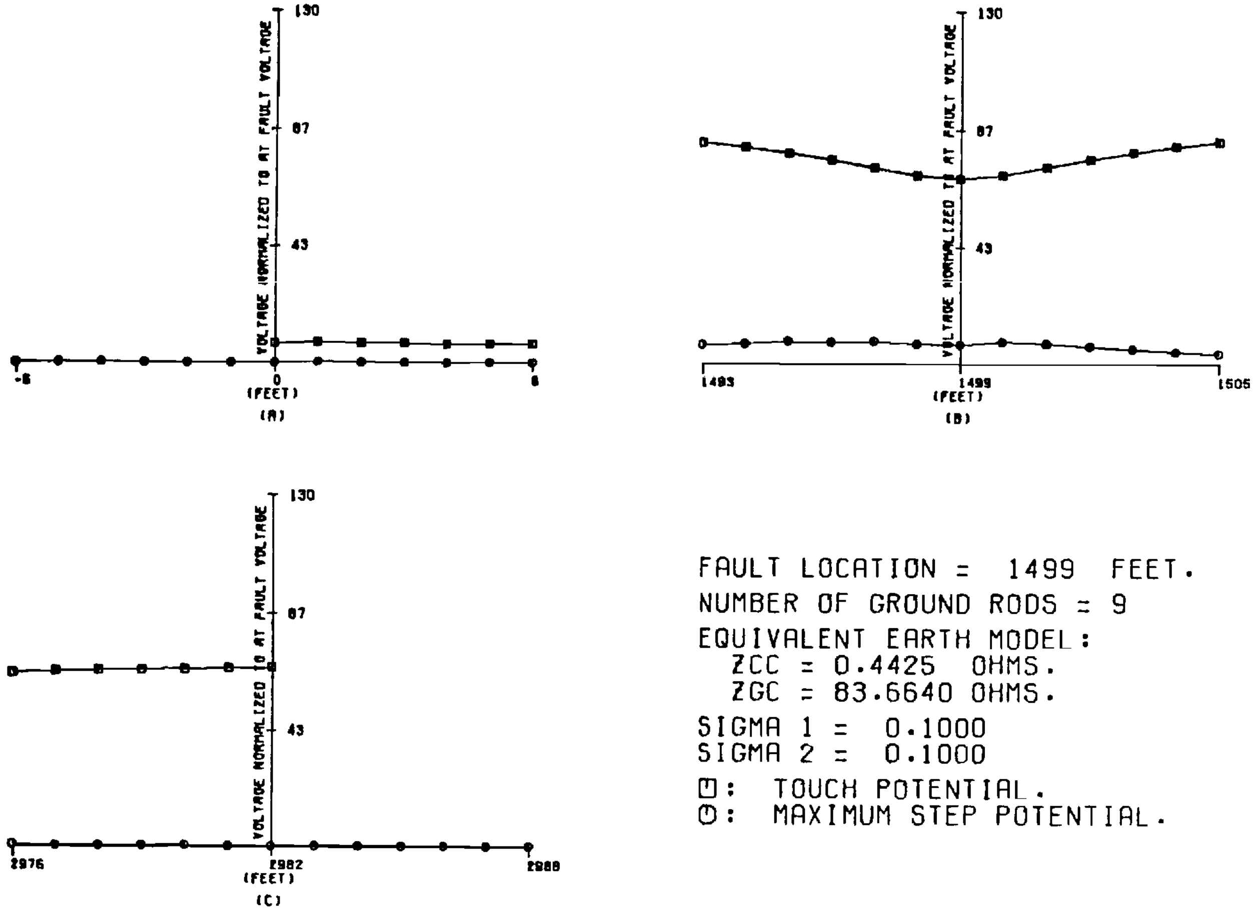


FIGURE A.98. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

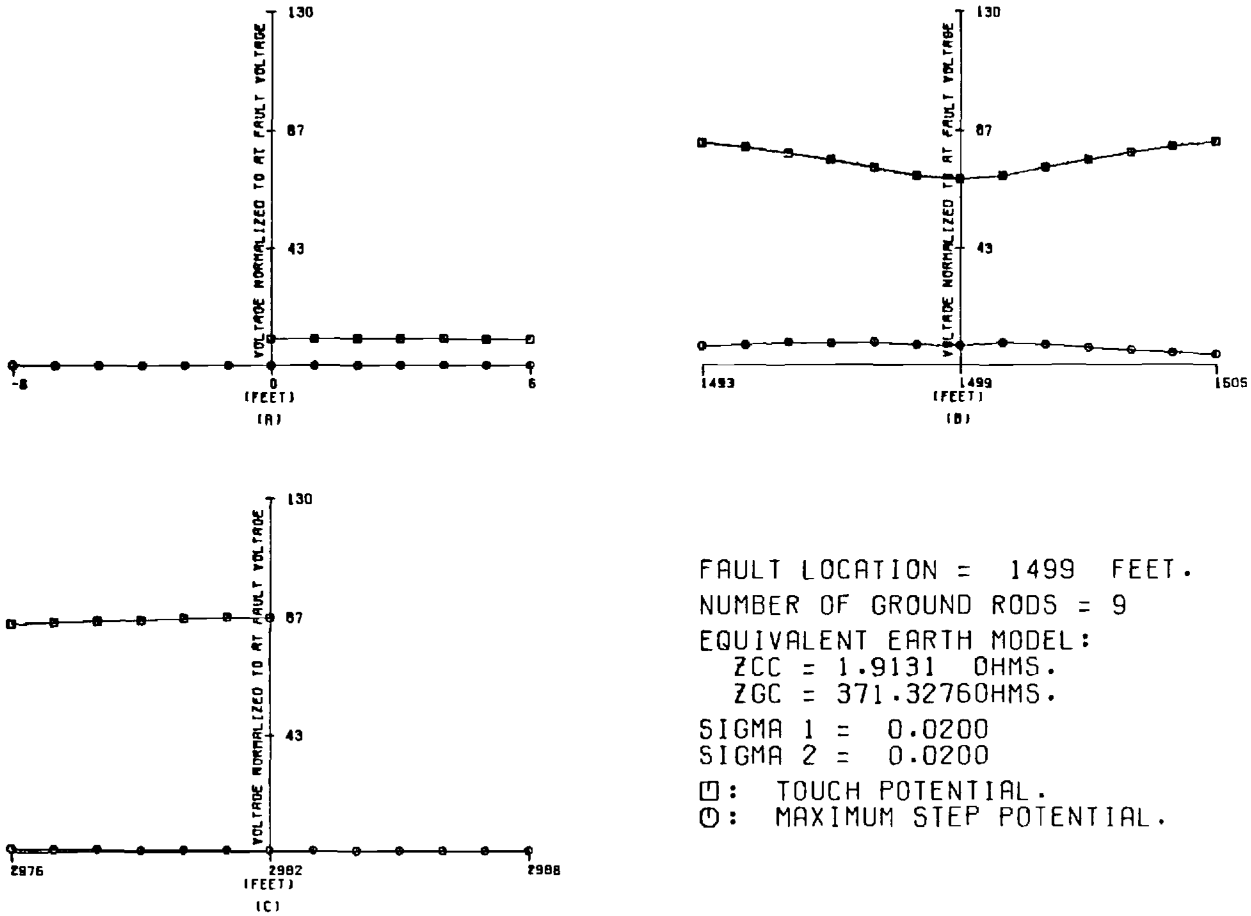


FIGURE A.99. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

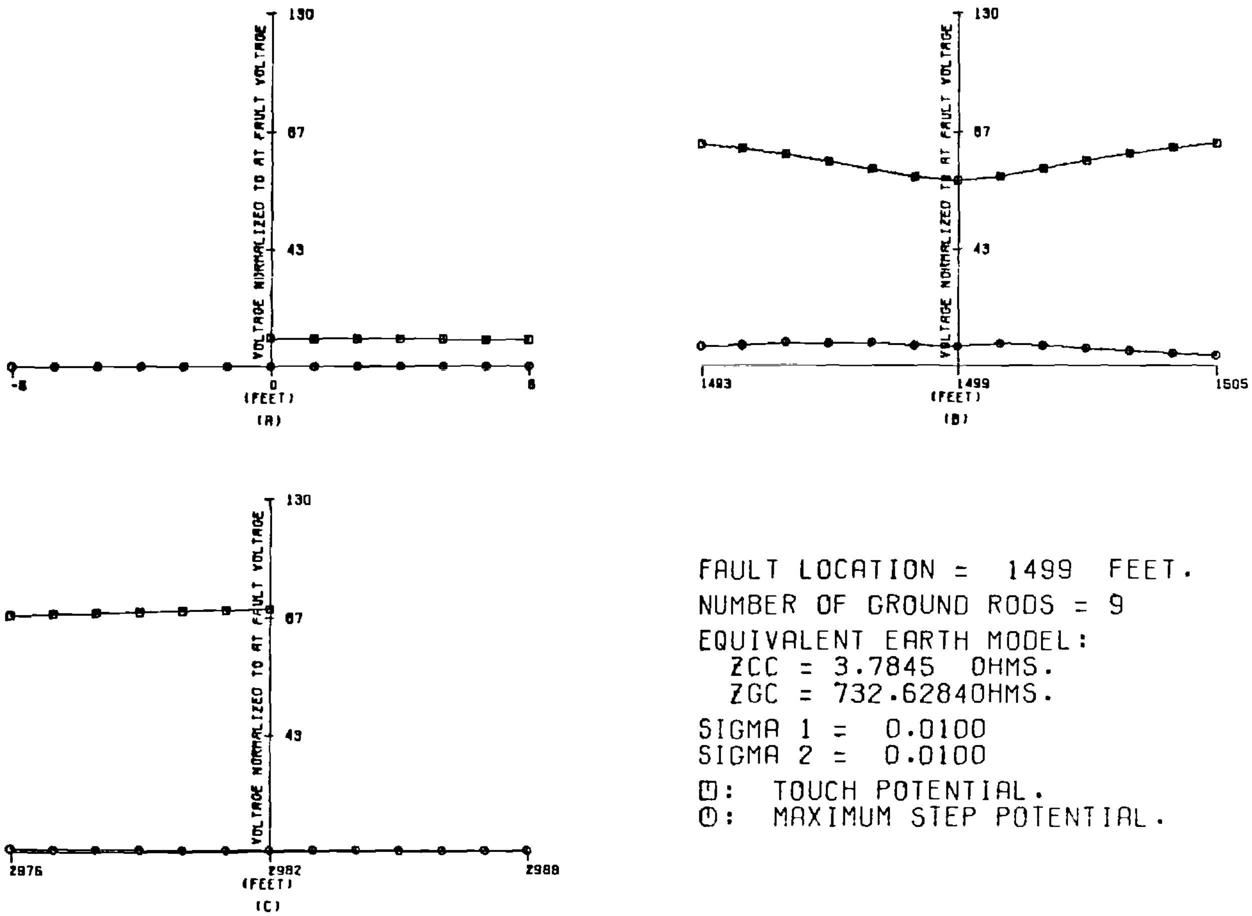


FIGURE A.100. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

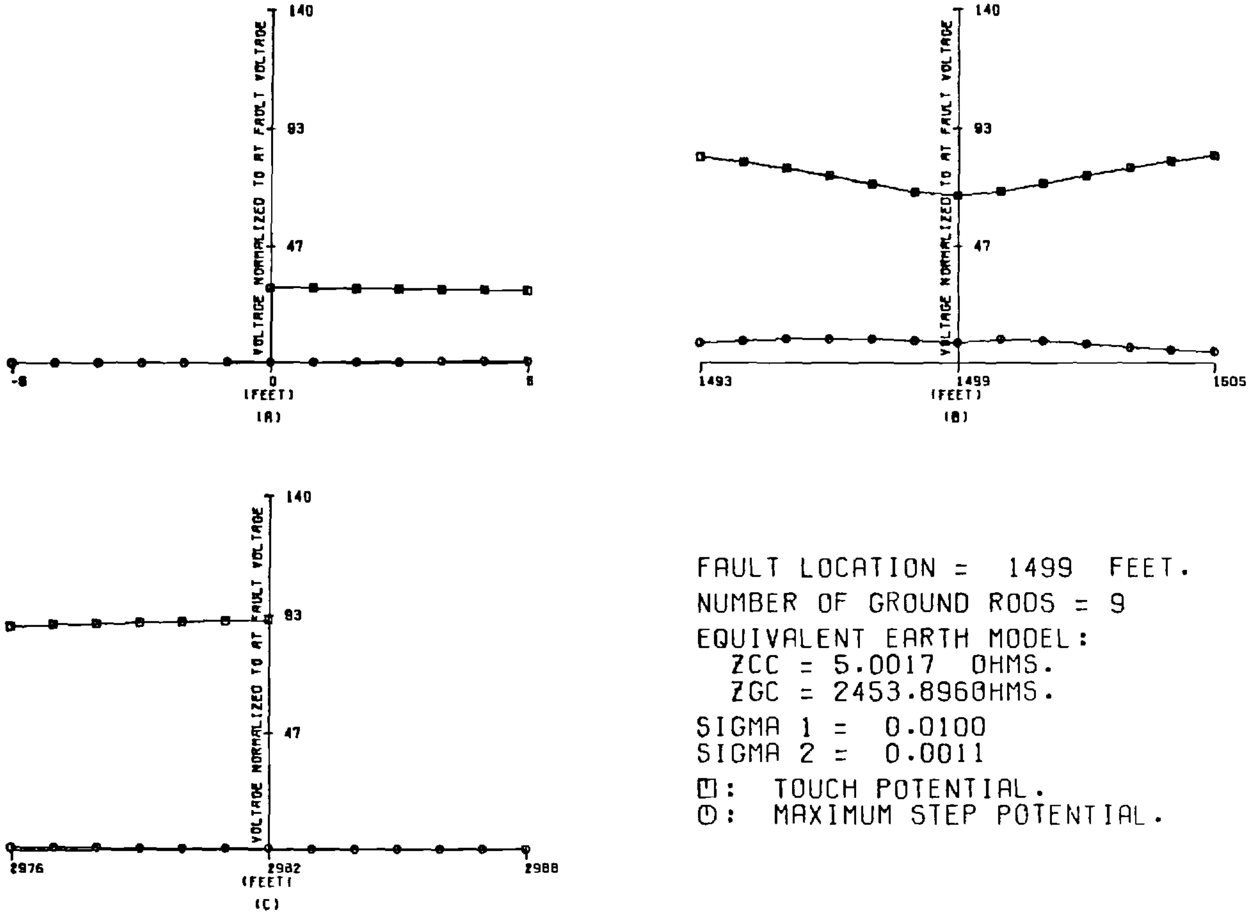


FIGURE A.101. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

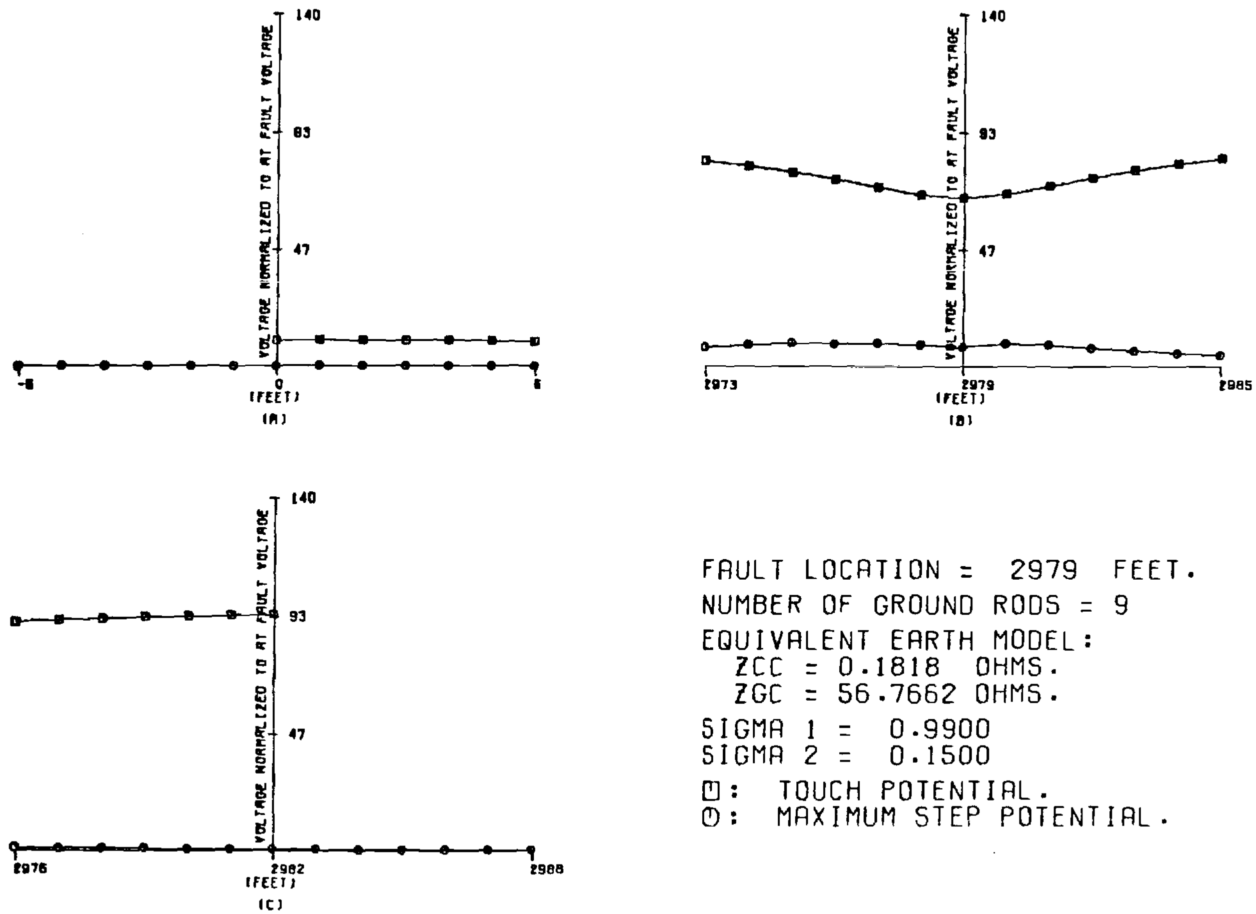


FIGURE A.102. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

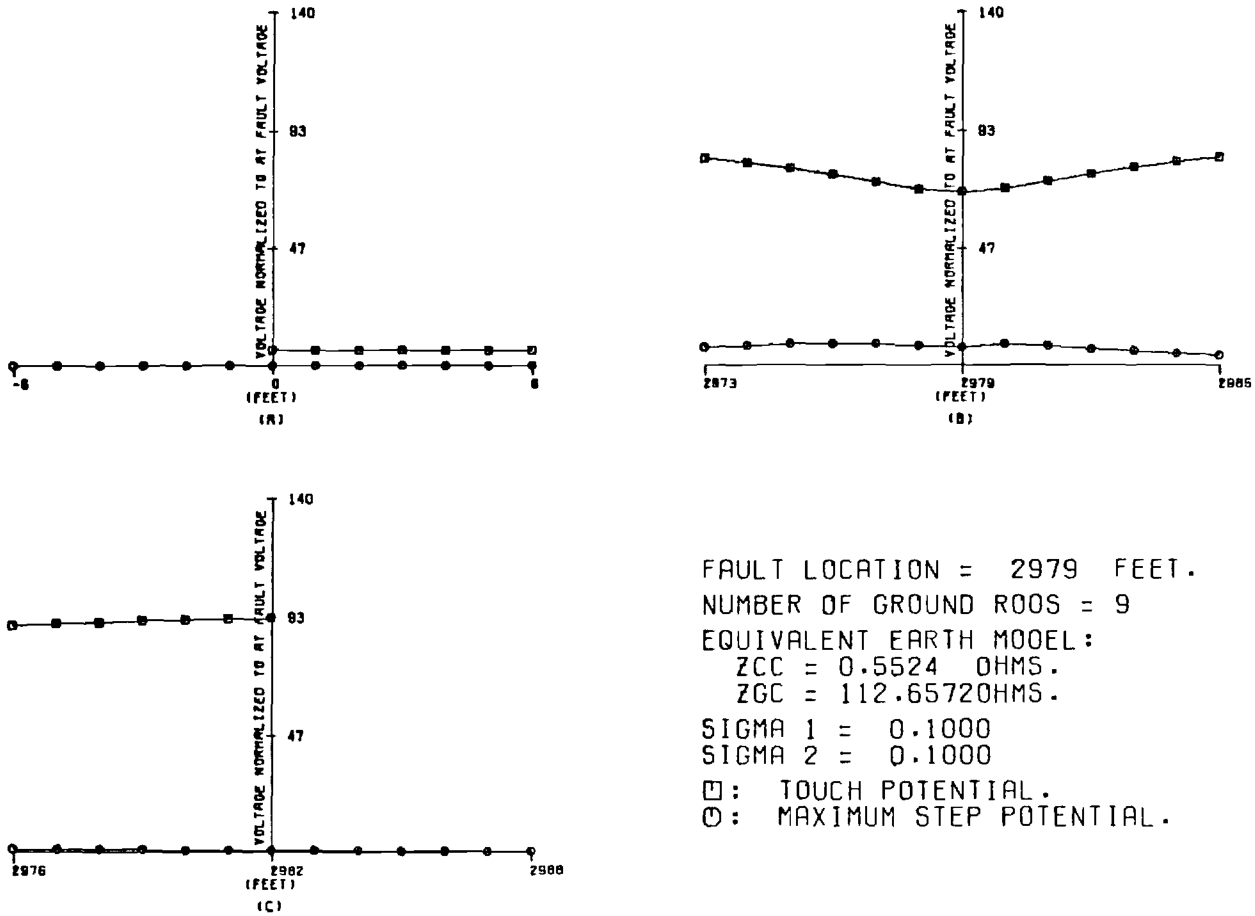
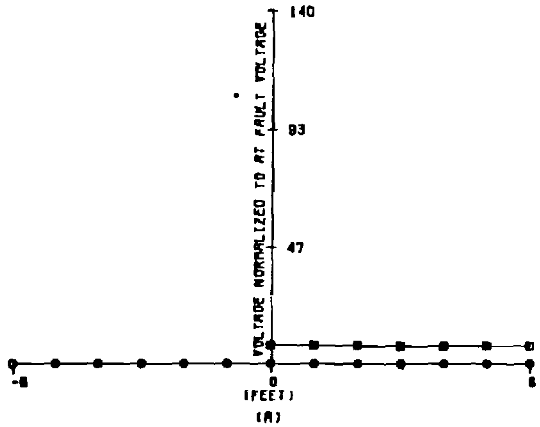
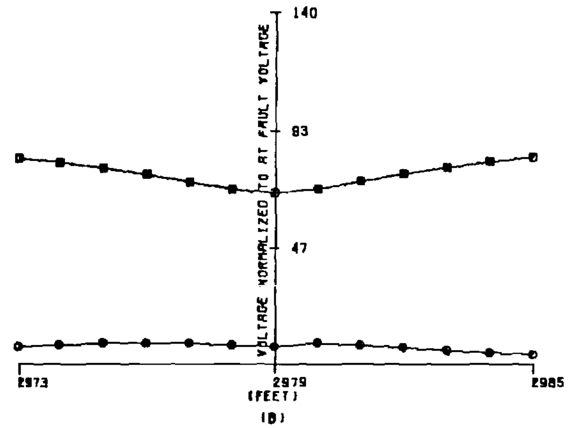
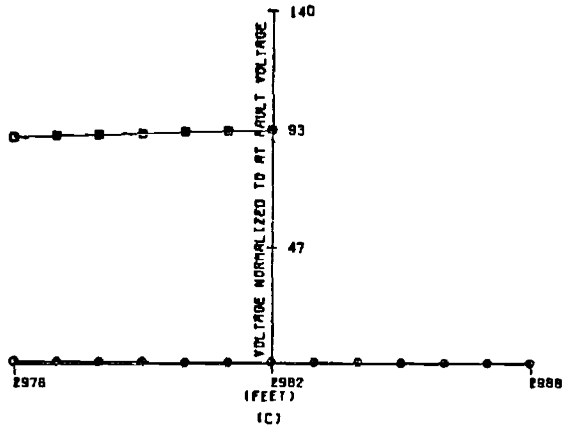


FIGURE A.103. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

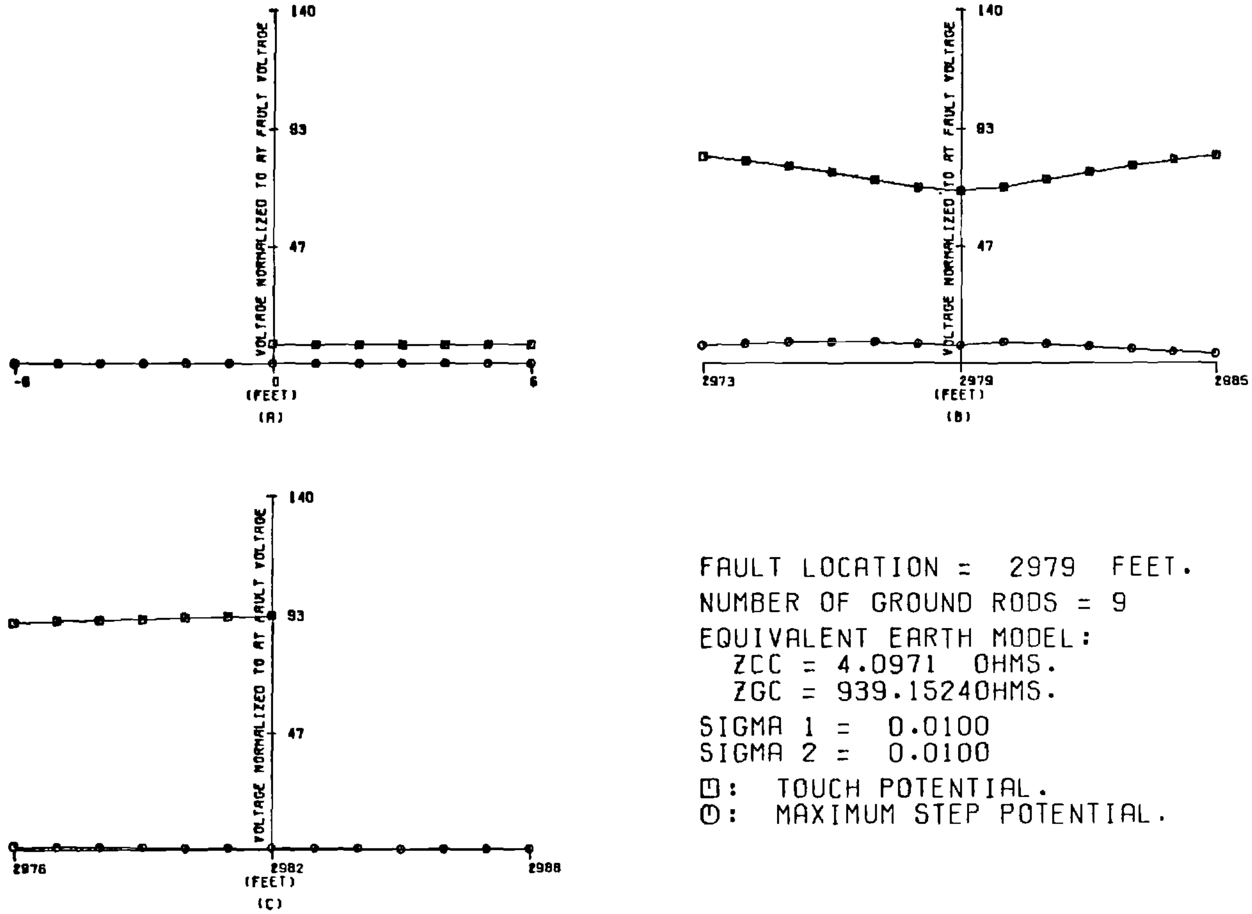






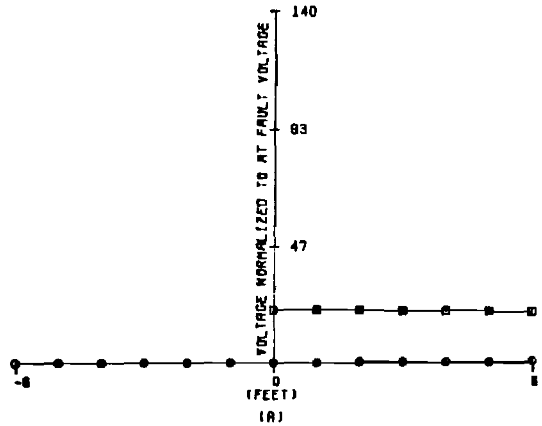
FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 2.1007 OHMS.
ZGC = 478.5085OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

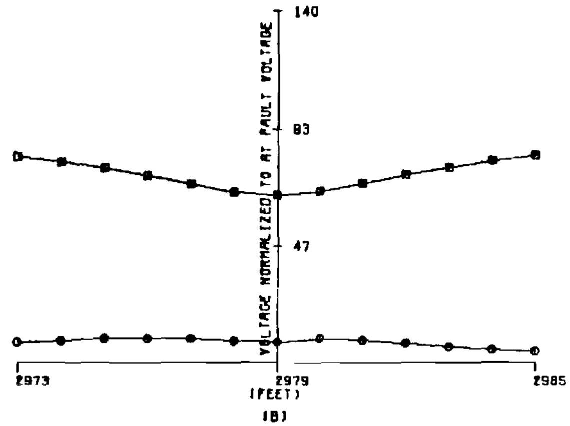
FIGURE A.104. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

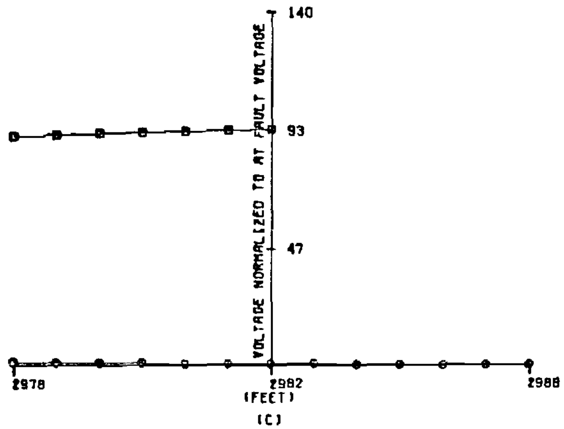


FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 4.0971 OHMS.
ZGC = 939.1524OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.105. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

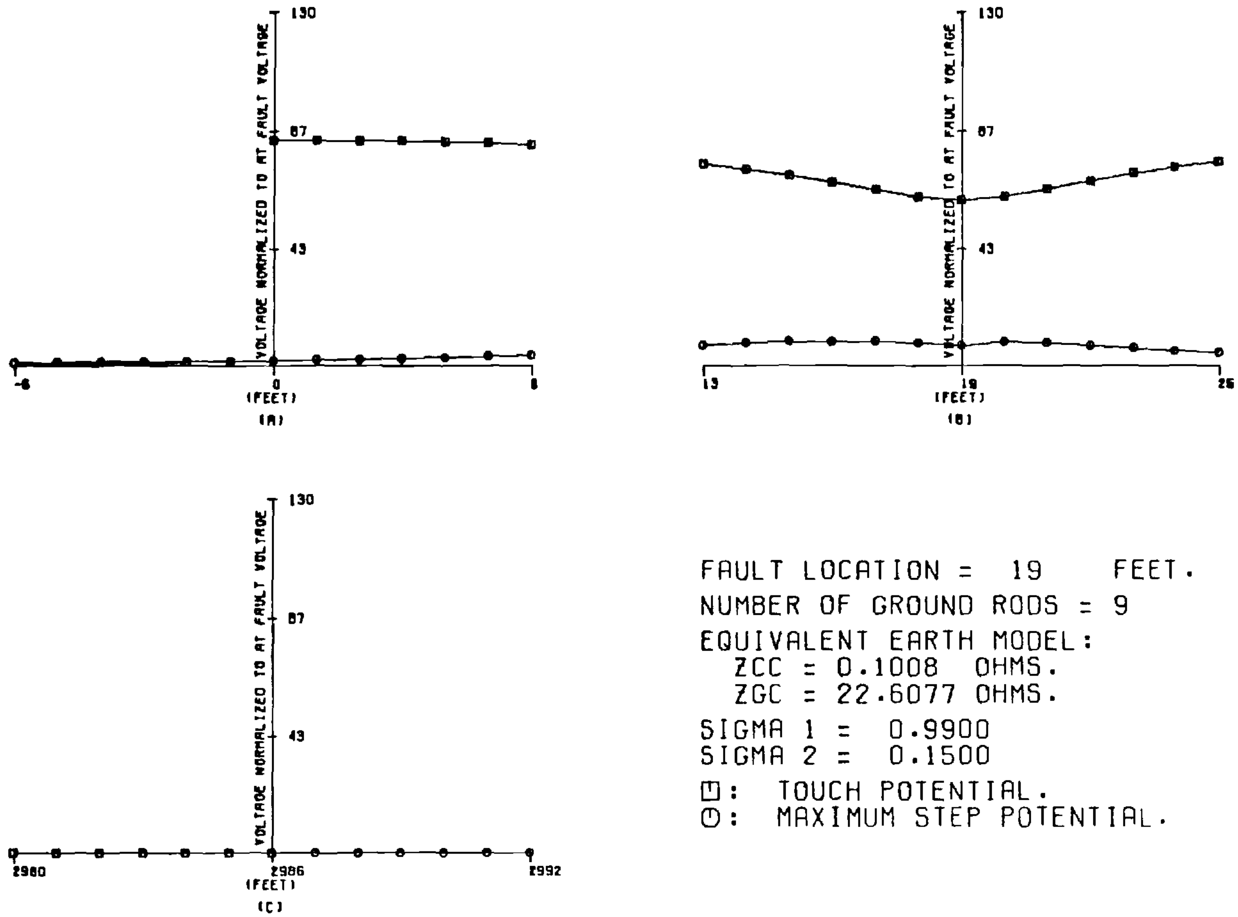






FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 5.7954 OHMS.
ZGC = 3202.822OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.106. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1008 OHMS.
ZGC = 22.6077 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.107. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

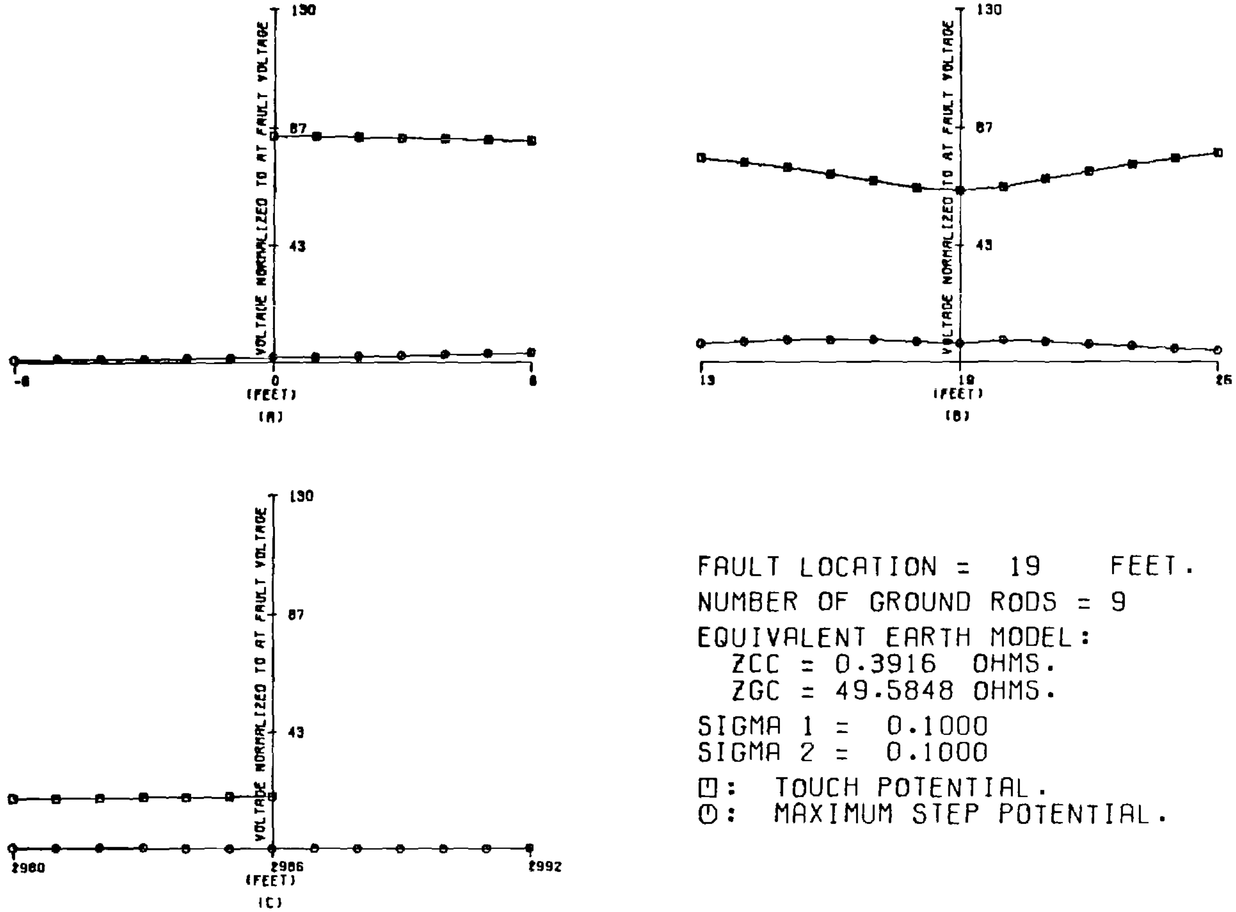


FIGURE A.108. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

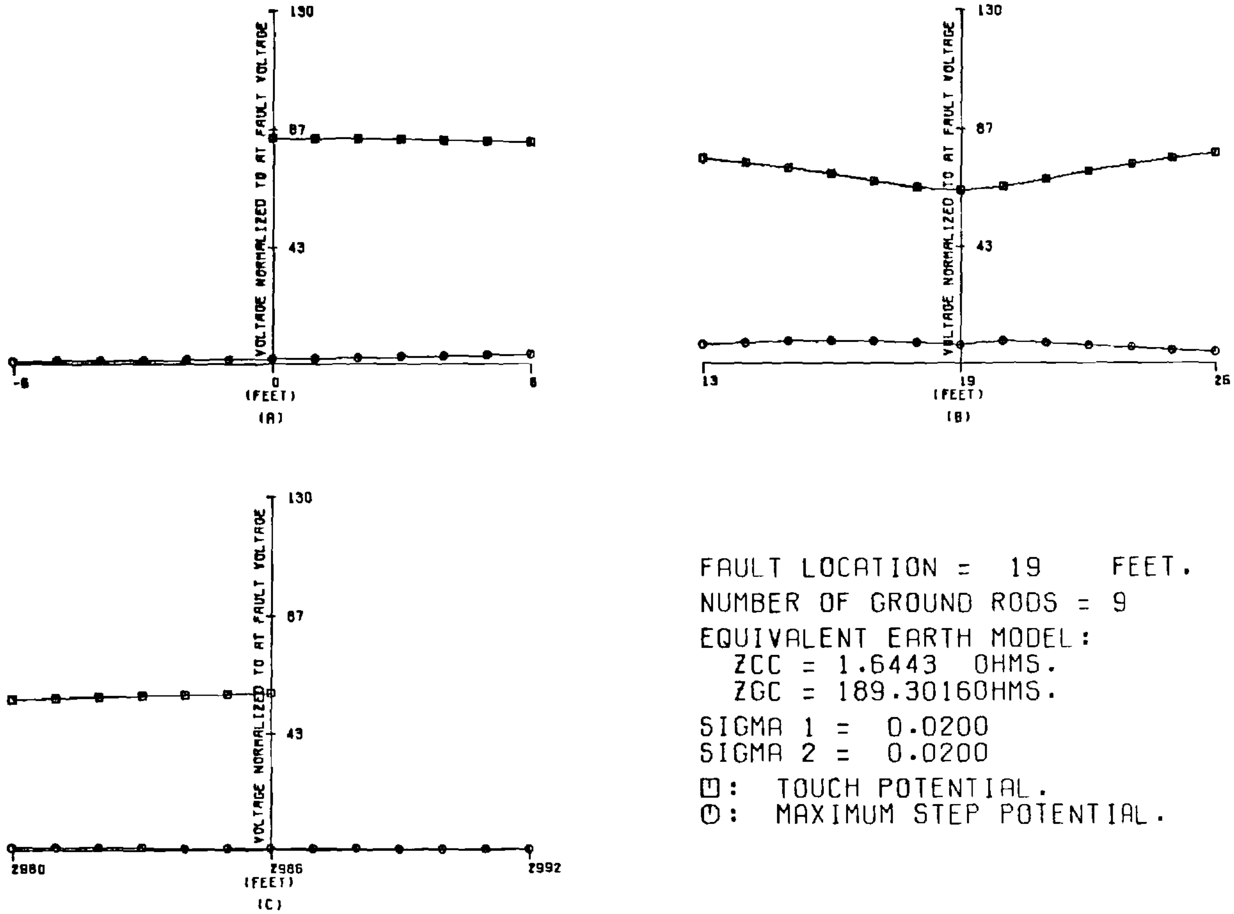


FIGURE A.109. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

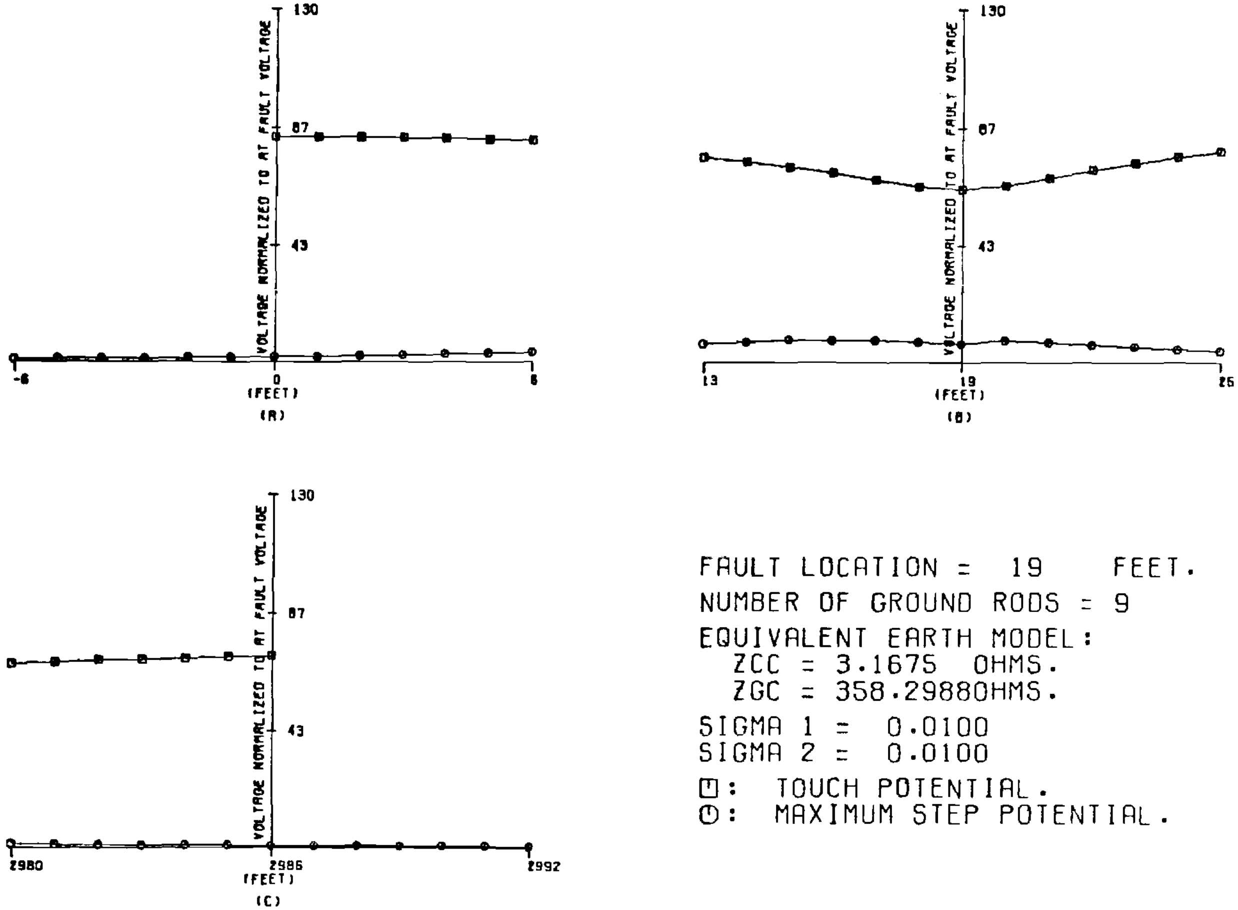


FIGURE A.110. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

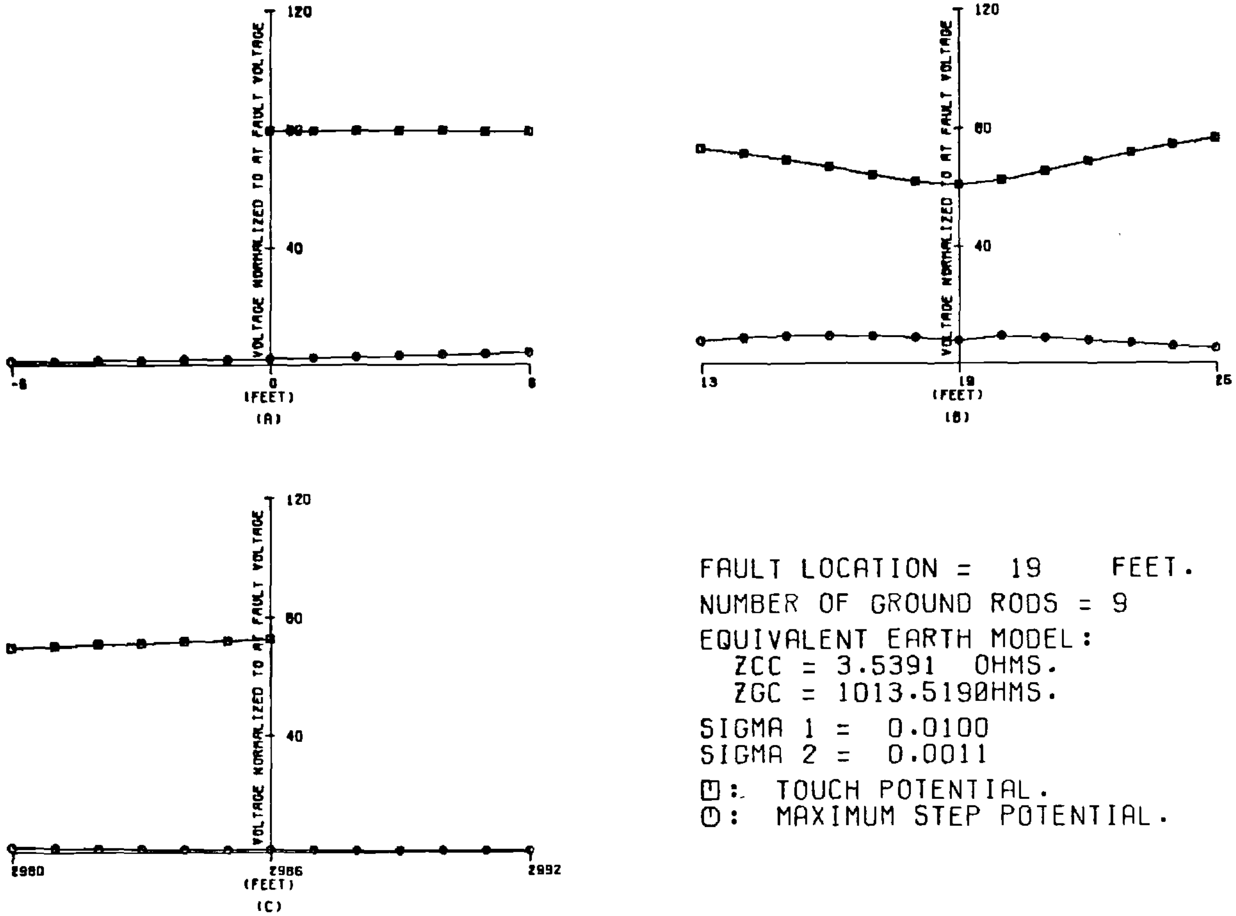
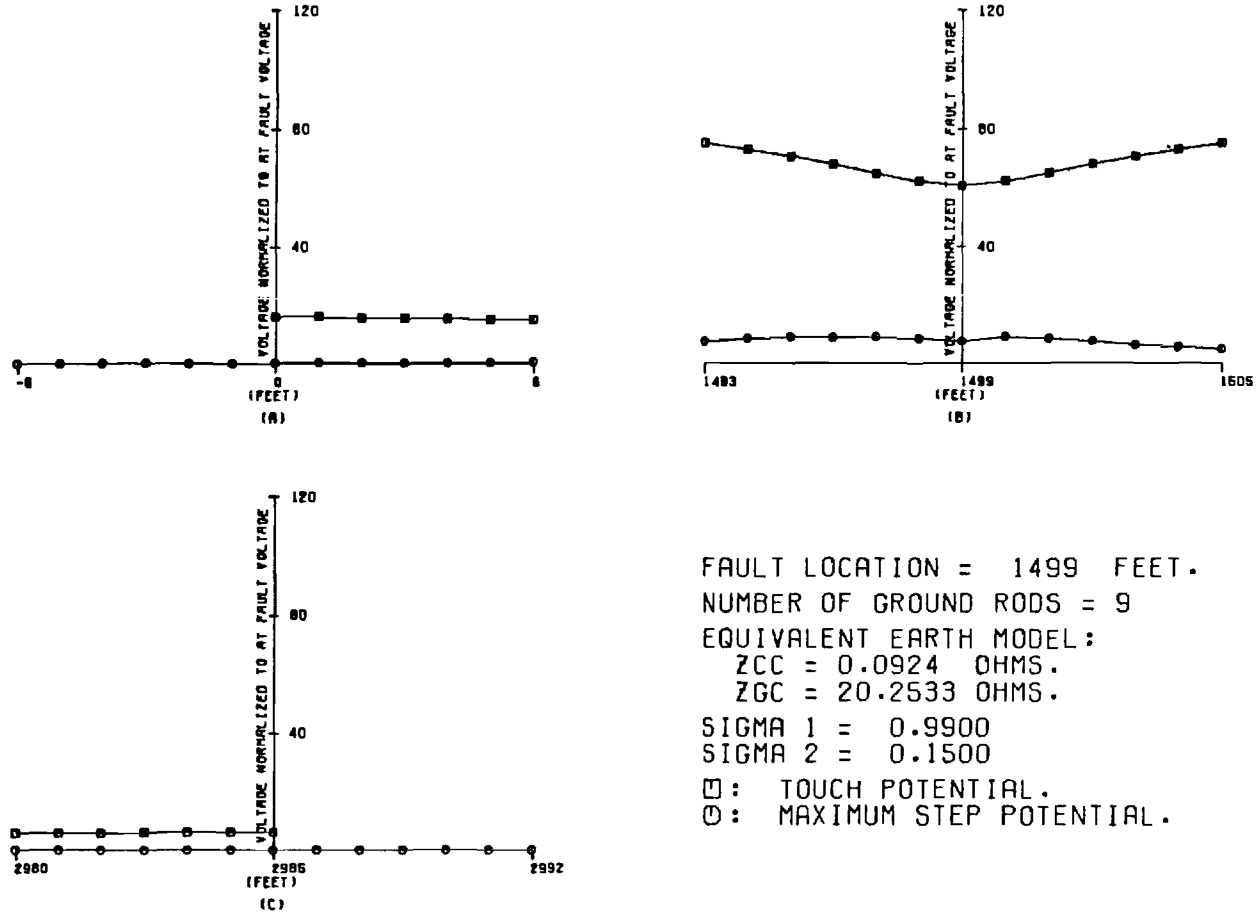


FIGURE A.111. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.0924 OHMS.
ZGC = 20.2533 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.112. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

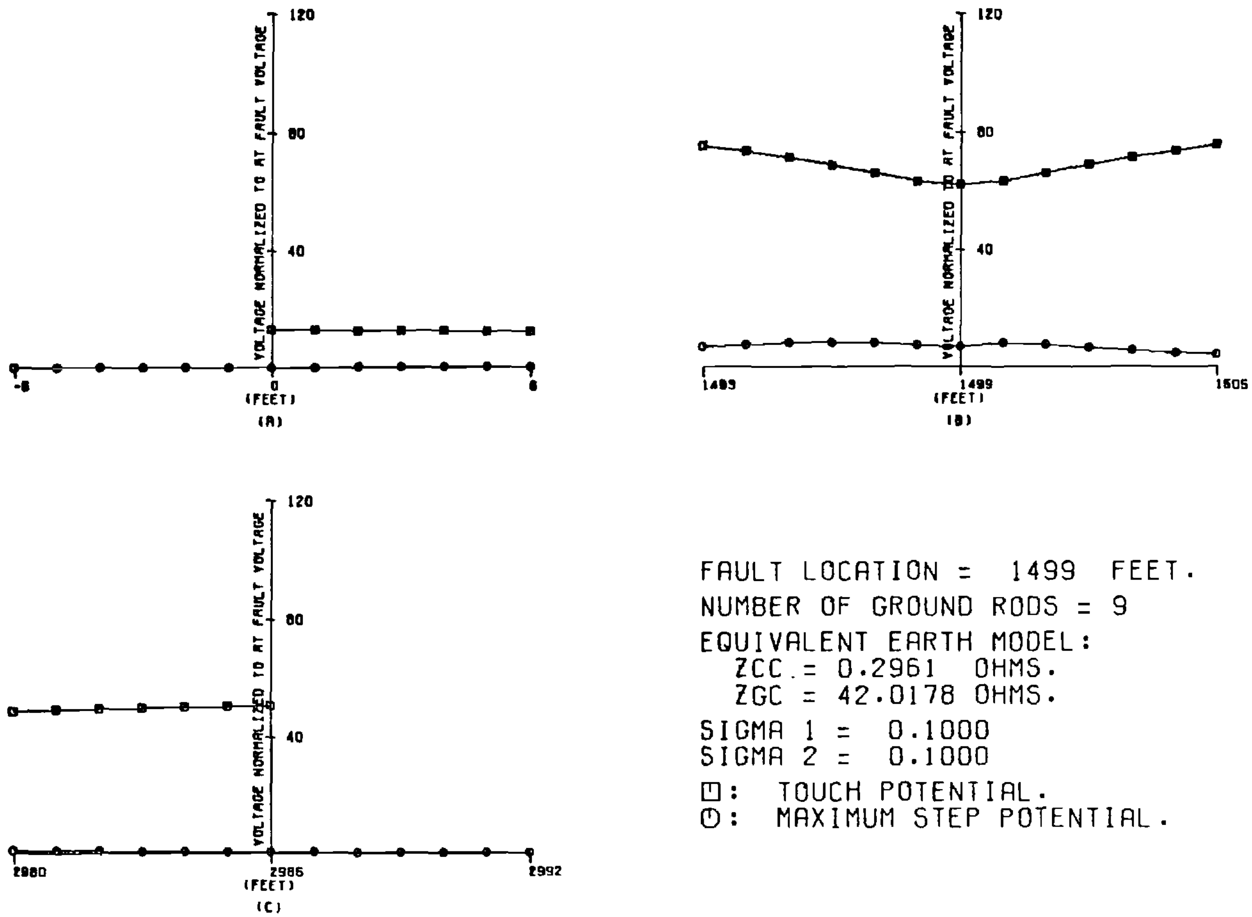
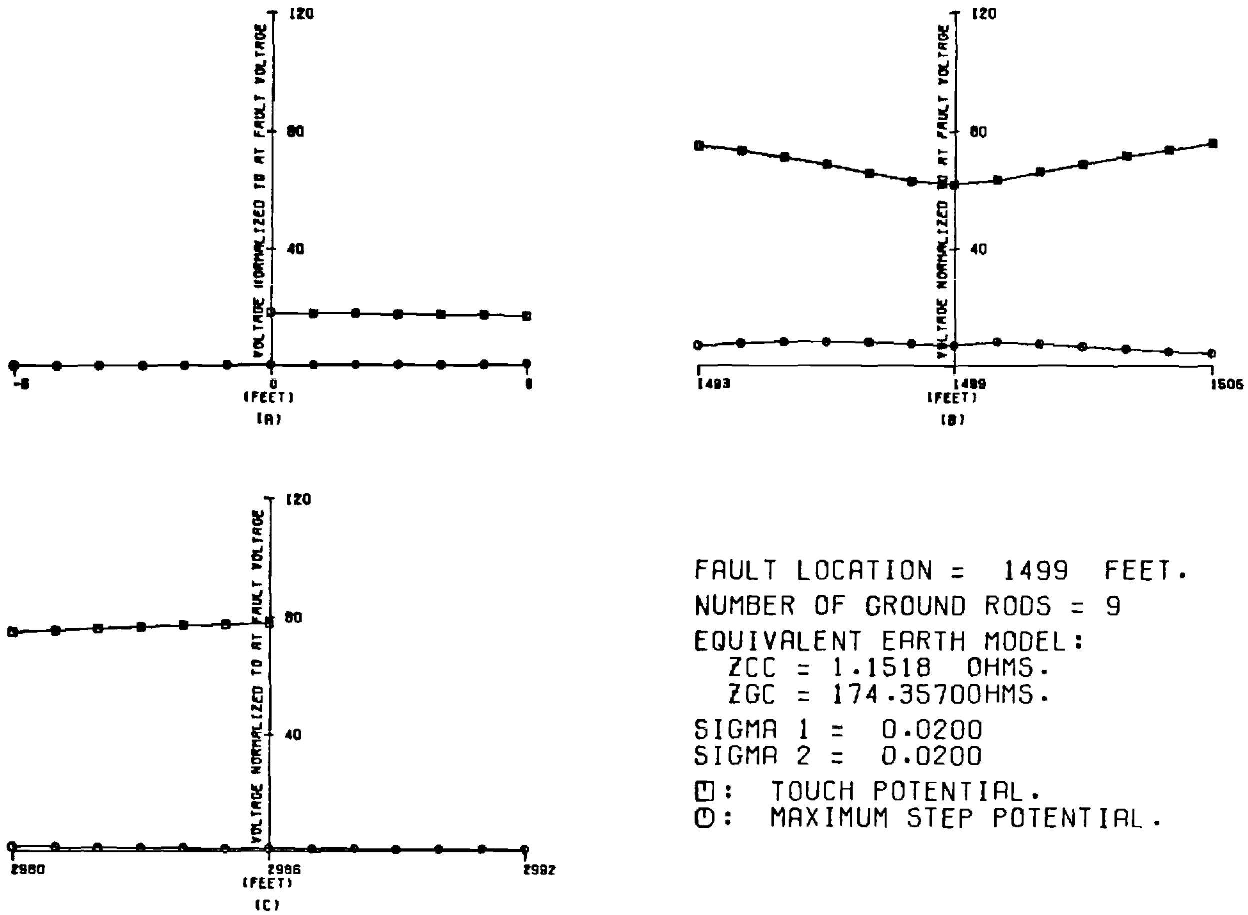


FIGURE A.113. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 1.1518 OHMS.
ZGC = 174.35700HMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.114. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

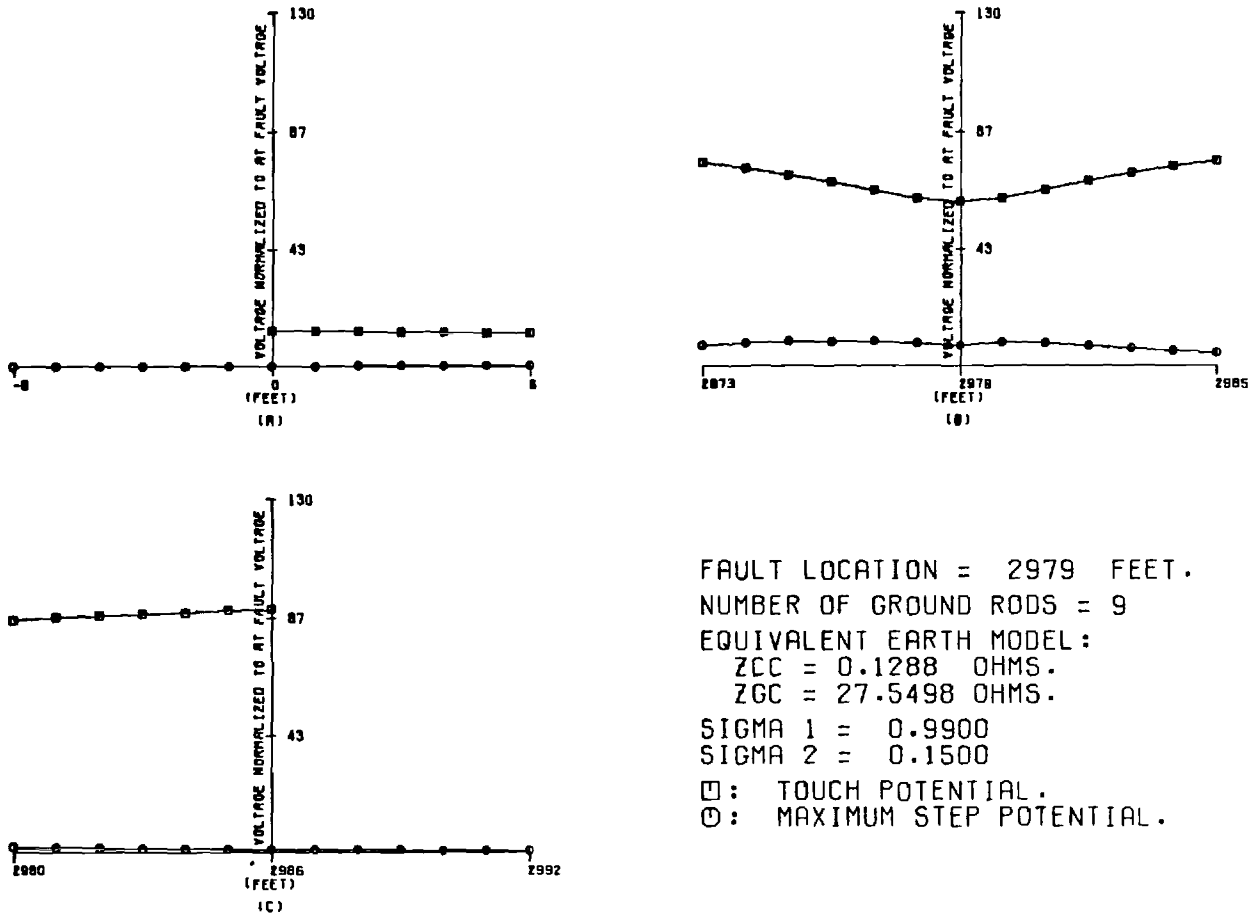
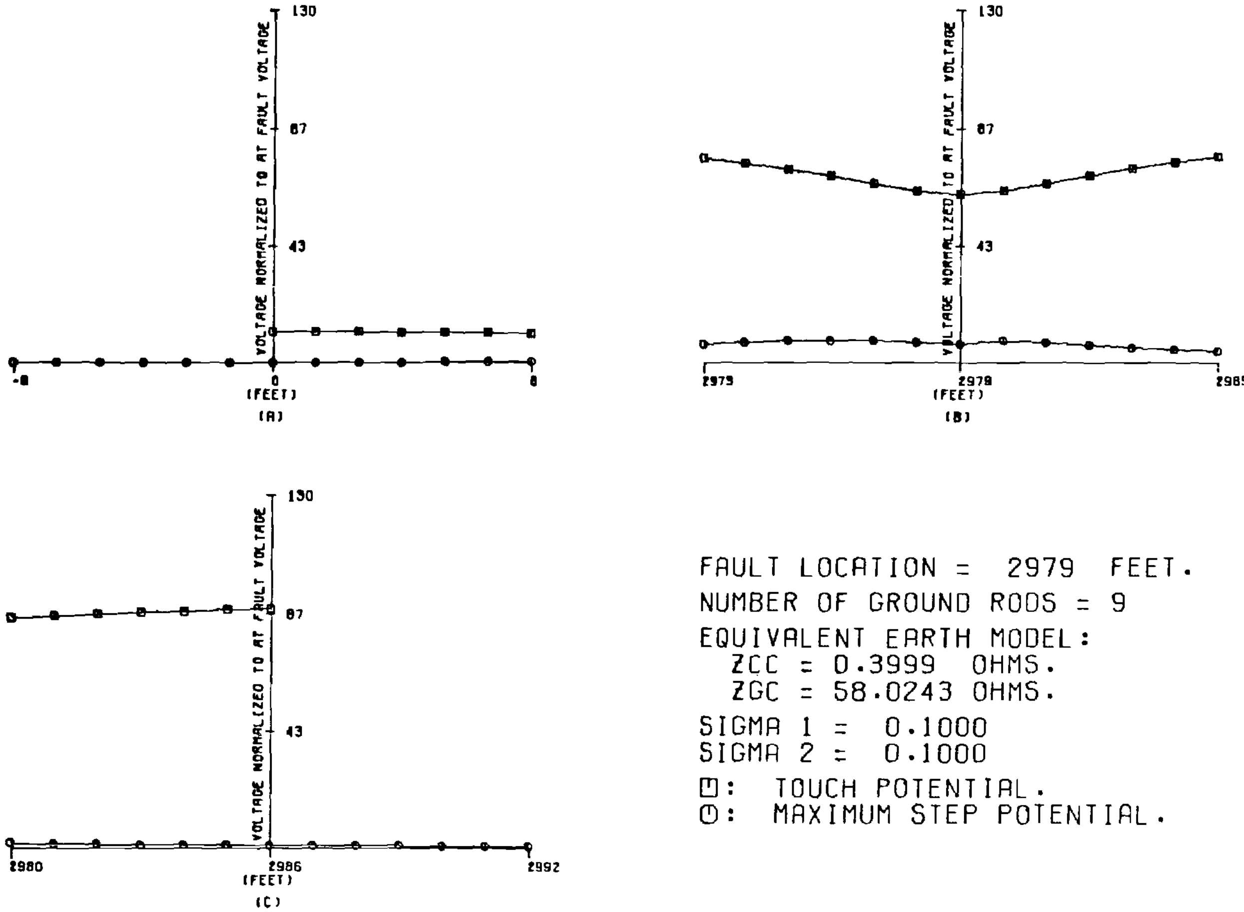
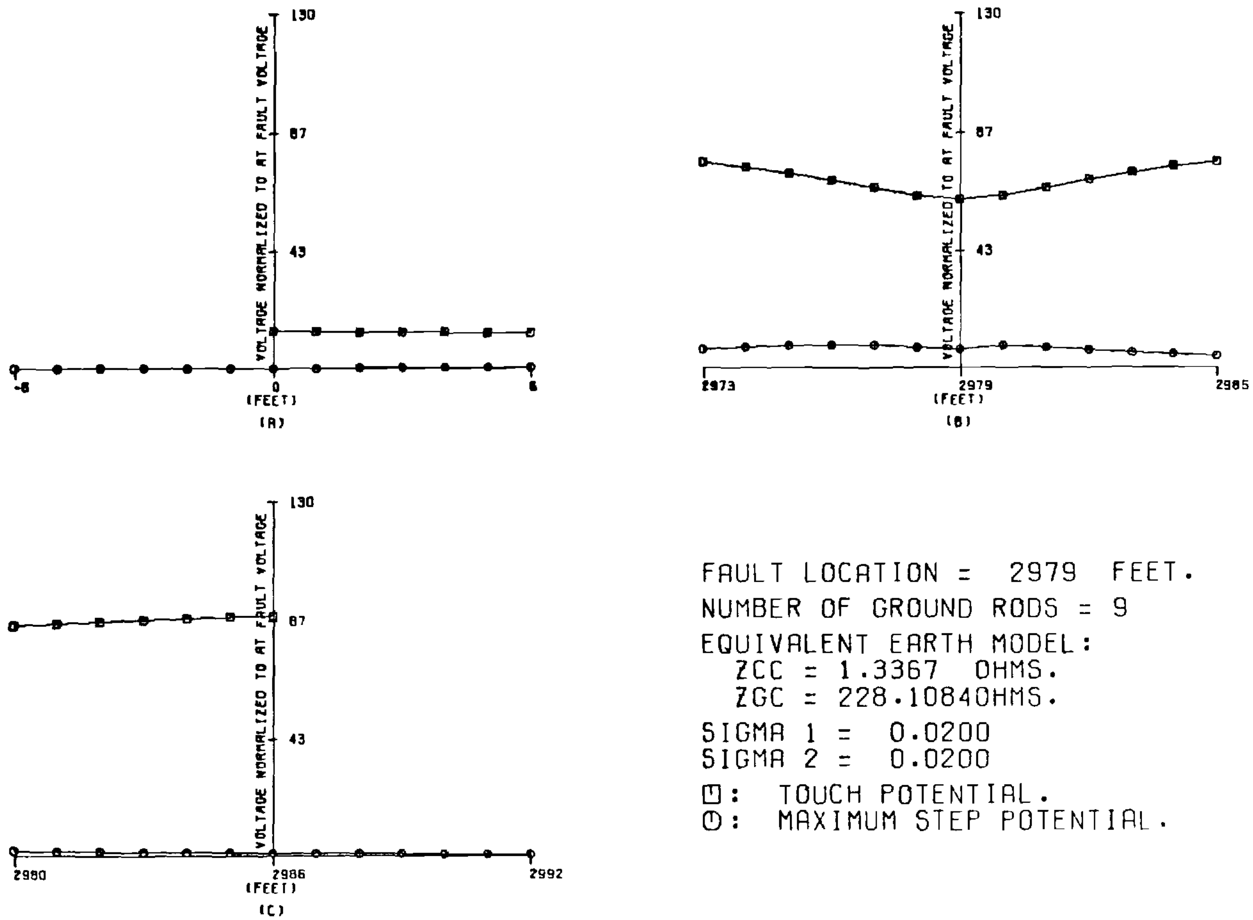


FIGURE A.117. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.3999 OHMS.
ZGC = 58.0243 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.118. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 1.3367 OHMS.
ZGC = 228.10840HMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE A.119. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

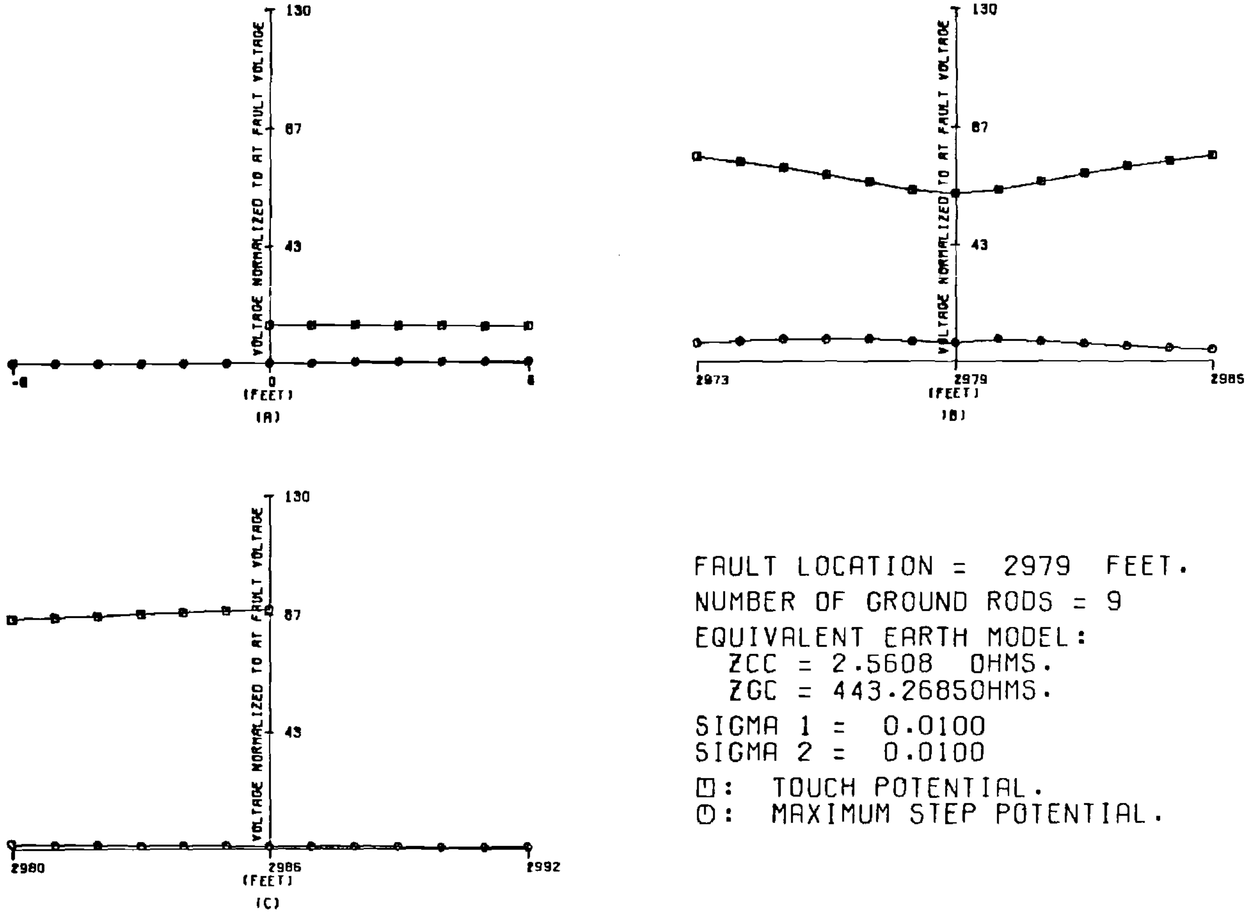
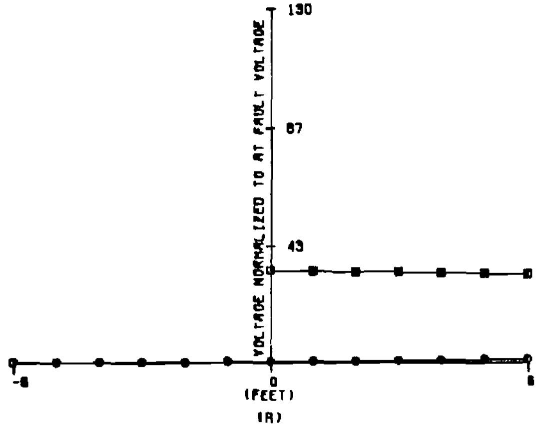
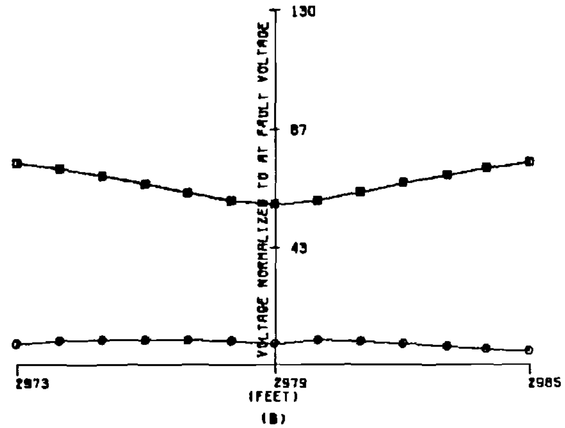
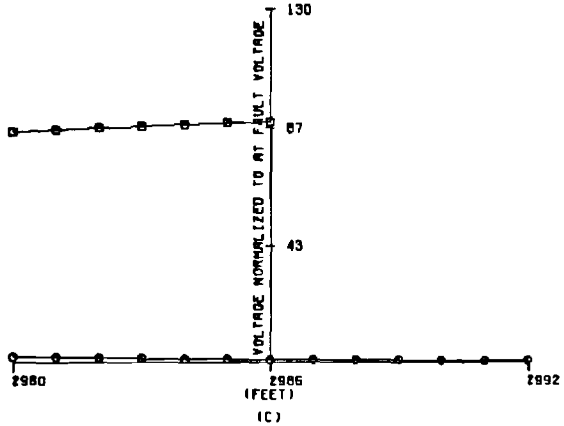


FIGURE A.120. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 3.7240 OHMS.
ZGC = 1401.065ØHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE A.121. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

Appendix II.B

GRAPHICAL RESULTS FOR BARE NEUTRAL AND SEMICONDUCTING JACKET CABLE

This appendix contains all the computer generated data for underground faulted cables with semiconducting jacket or bare. Table B.1 summarizes the organization of the data for quick reference. Additional information, i.e. soil resistivity or conductivity, fault location, etc., is given in individual figures.

Table B.1

BARE NEUTRAL AND SEMICONDUCTING JACKET CABLE

Figures B.1 through B.21
Ground Rods 9 x 16 ft.
Burial Depth 30"

	σ_1	σ_2	Fault: Source End	Fault: Center	Fault: Remote End
B.1	.99	.15	X		
B.2	.1	.02	X		
B.3	.1	.1	X		
B.4	.02	.02	X		
B.5	.02	.005	X		
B.6	.01	.01	X		
B.7	.01	.0011	X		
B.8	.99	.15		X	
B.9	.1	.02		X	
B.10	.1	.1		X	
B.11	.02	.02		X	
B.12	.02	.005		X	
B.13	.01	.01		X	
B.14	.01	.0011		X	
B.15	.99	.15			X
B.16	.1	.02			X
B.17	.1	.1			X
B.18	.02	.02			X
B.19	.02	.005			X
B.20	.01	.01			X
B.21	.01	.0011			X

Figures B.22 through B.42
Ground Rods 0
Burial Depth 30"

	σ_1	σ_2	Fault: Source End	Fault: Center	Fault: Remote End
B.22	.99	.15	X		
B.23	.1	.02	X		
B.24	.1	.1	X		
B.25	.02	.02	X		
B.26	.02	.005	X		
B.27	.01	.01	X		
B.28	.01	.0011	X		
B.29	.99	.15		X	
B.30	.1	.02		X	
B.31	.1	.1		X	
B.32	.02	.02		X	
B.33	.02	.005		X	
B.34	.01	.01		X	
B.35	.01	.0011		X	
B.36	.99	.15			X
B.37	.1	.02			X

			Source End	Center	Remote End
B.38	.1	.1			X
B.39	.02	.02			X
B.40	.02	.005			X
B.41	.01	.01			X
B.42	.01	.0011			X

Figures B.43 through B.63
Ground Rods 9 x 16 ft.
Burial Depth 36"

	σ_1	σ_2	Fault: Source End	Center	Remote End
B.43	.99	.15	X		
B.44	.1	.02	X		
B.45	.1	.1	X		
B.46	.02	.02	X		
B.47	.02	.005	X		
B.48	.01	.01	X		
B.49	.01	.0011	X		
B.50	.99	.15		X	
B.51	.1	.02		X	
B.52	.1	.1		X	
B.53	.02	.02		X	
B.54	.02	.005		X	
B.55	.01	.01		X	
B.56	.01	.0011		X	
B.57	.99	.15			X
B.58	.1	.02			X
B.59	.1	.1			X
B.60	.02	.02			X
B.61	.02	.005			X
B.62	.01	.01			X
B.63	.01	.0011			X

Figures B.64 through 84
Ground Rods 0
Burial Depth 36"

			Source End	Center	Remote End
B.64	.99	.15	X		
B.65	.1	.02	X		
B.66	.1	.1	X		
B.67	.02	.02	X		
B.68	.02	.005	X		
B.69	.01	.01	X		
B.70	.01	.0011	X		
B.71	.99	.15		X	
B.72	.1	.02		X	
B.73	.1	.1		X	
B.74	.02	.02		X	
B.75	.02	.005		X	
B.76	.01	.01		X	
B.77	.01	.0011		X	
B.78	.99	.15			X
B.79	.1	.02			X
B.80	.1	.1			X
B.81	.02	.02			X

B.82	.02	.005			X
B.83	.01	.01			X
B.84	.01	.0011			X

Figures B.85 through 105
Ground Rods 9 x 16 ft.
Burial Depth 42"

			Fault		
	σ_1	σ_2	Source End	Center	Remote End
B.85	.99	.15	X		
B.86	.1	.02	X		
B.87	.1	.1	X		
B.88	.02	.02	X		
B.89	.02	.005	X		
B.90	.01	.01	X		
B.91	.01	.0011	X		
B.92	.99	.15		X	
B.93	.1	.02		X	
B.94	.1	.1		X	
B.95	.02	.02		X	
B.96	.02	.005		X	
B.97	.01	.01		X	
B.98	.01	.0011		X	
B.99	.99	.15			X
B.100	.1	.02			X
B.101	.1	.1			X
B.102	.02	.02			X
B.103	.02	.005			X
B.104	.01	.01			X
B.105	.01	.0011			X

Figures B.106 through 126
Ground Rods 0
Burial Depth 42"

B.106	.99	.15	X		
B.107	.1	.02	X		
B.108	.1	.1	X		
B.109	.02	.02	X		
B.110	.02	.005	X		
B.111	.01	.01	X		
B.112	.01	.0011	X		
B.113	.99	.15		X	
B.114	.1	.02		X	
B.115	.1	.1		X	
B.116	.02	.02		X	
B.117	.02	.005		X	
B.118	.01	.01		X	
B.119	.01	.0011		X	
B.120	.99	.15			X
B.121	.1	.02			X
B.122	.1	.1			X
B.123	.02	.02			X
B.124	.02	.005			X
B.126	.01	.0011			X
B.125	.01	.01			X

Figures B.127 through 147
Ground Rods 9 x 16 ft.
Burial Depth 48"

	σ_1	σ_2	Fault: Source End	Center	Remote End
B.127	.99	.15	X		
B.128	.1	.02	X		
B.129	.1	.1	X		
B.130	.02	.02	X		
B.131	.02	.005	X		
B.132	.01	.01	X		
B.133	.01	.0011	X		
B.134	.99	.15		X	
B.135	.1	.02		X	
B.136	.1	.1		X	
B.137	.02	.02		X	
B.138	.02	.005		X	
B.139	.01	.01		X	
B.140	.01	.0011		X	
B.141	.99	.15			X
B.142	.1	.02			X
B.143	.1	.1			X
B.144	.02	.02			X
B.145	.02	.005			X
B.146	.01	.01			X
B.147	.01	.0011			X

Figures B.148 through 168
Ground Rods 0
Burial Depth 48"

	σ_1	σ_2	Source End	Center	Remote End
B.148	.99	.15	X		
B.149	.1	.02	X		
B.150	.1	.1	X		
B.151	.02	.02	X		
B.152	.02	.005	X		
B.153	.01	.01	X		
B.154	.01	.0011	X		
B.155	.99	.15		X	
B.156	.1	.02		X	
B.157	.1	.1		X	
B.158	.02	.02		X	
B.159	.02	.005		X	
B.160	.01	.01		X	
B.161	.01	.0011		X	
B.162	.99	.15			X
B.163	.1	.02			X
B.164	.1	.1			X
B.165	.02	.02			X
B.166	.02	.005			X
B.167	.01	.01			X
B.168	.01	.0011			X

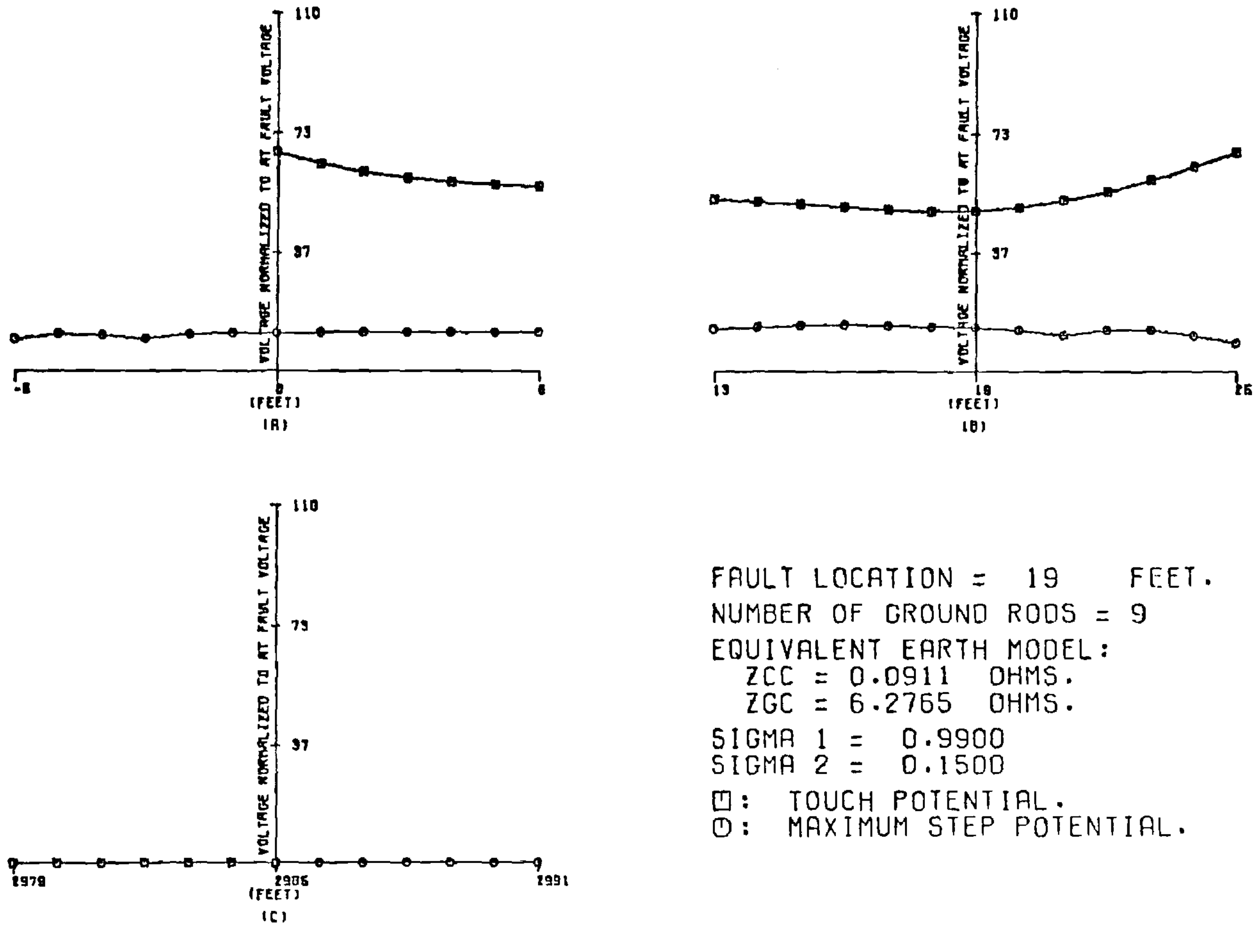


FIGURE B.1. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

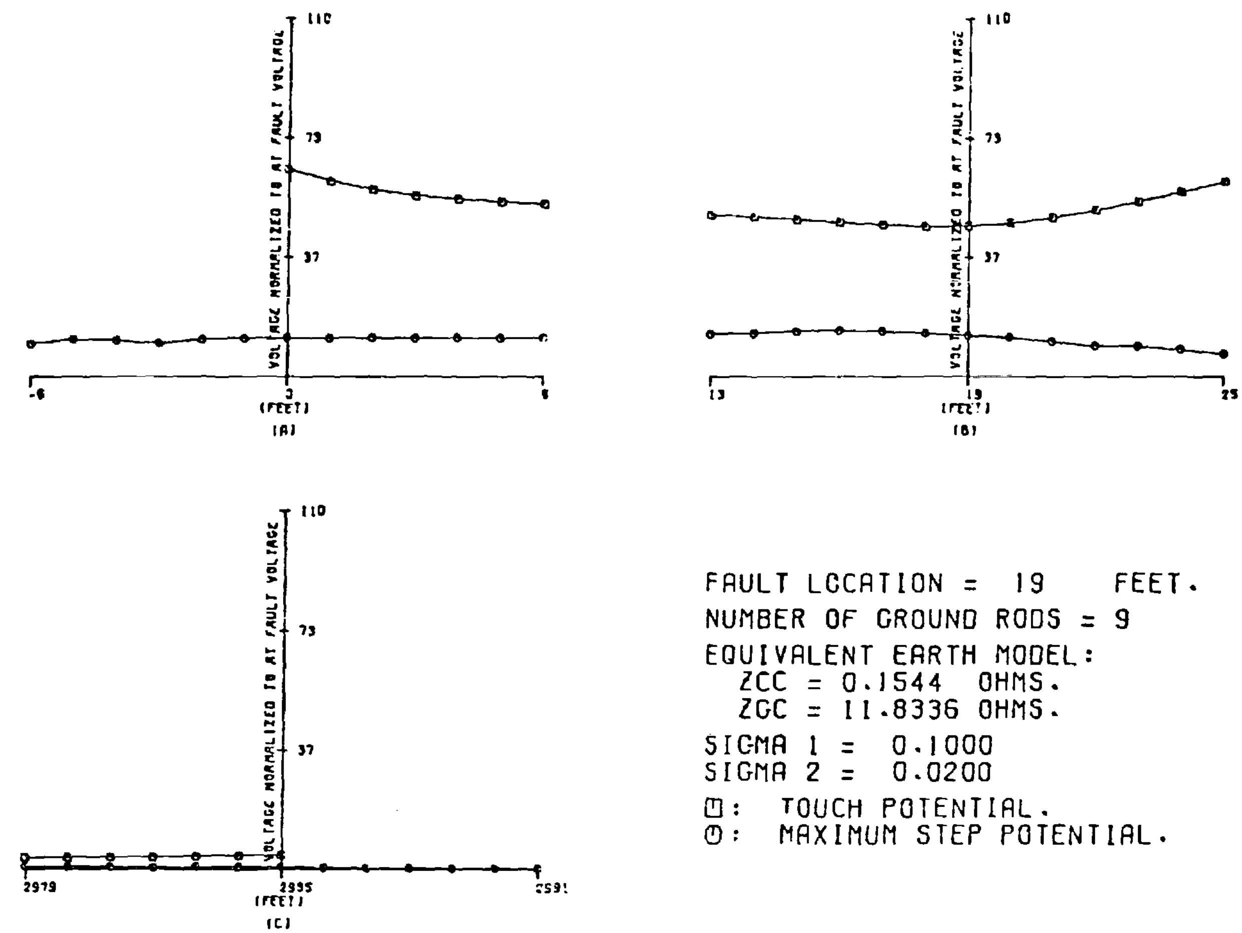
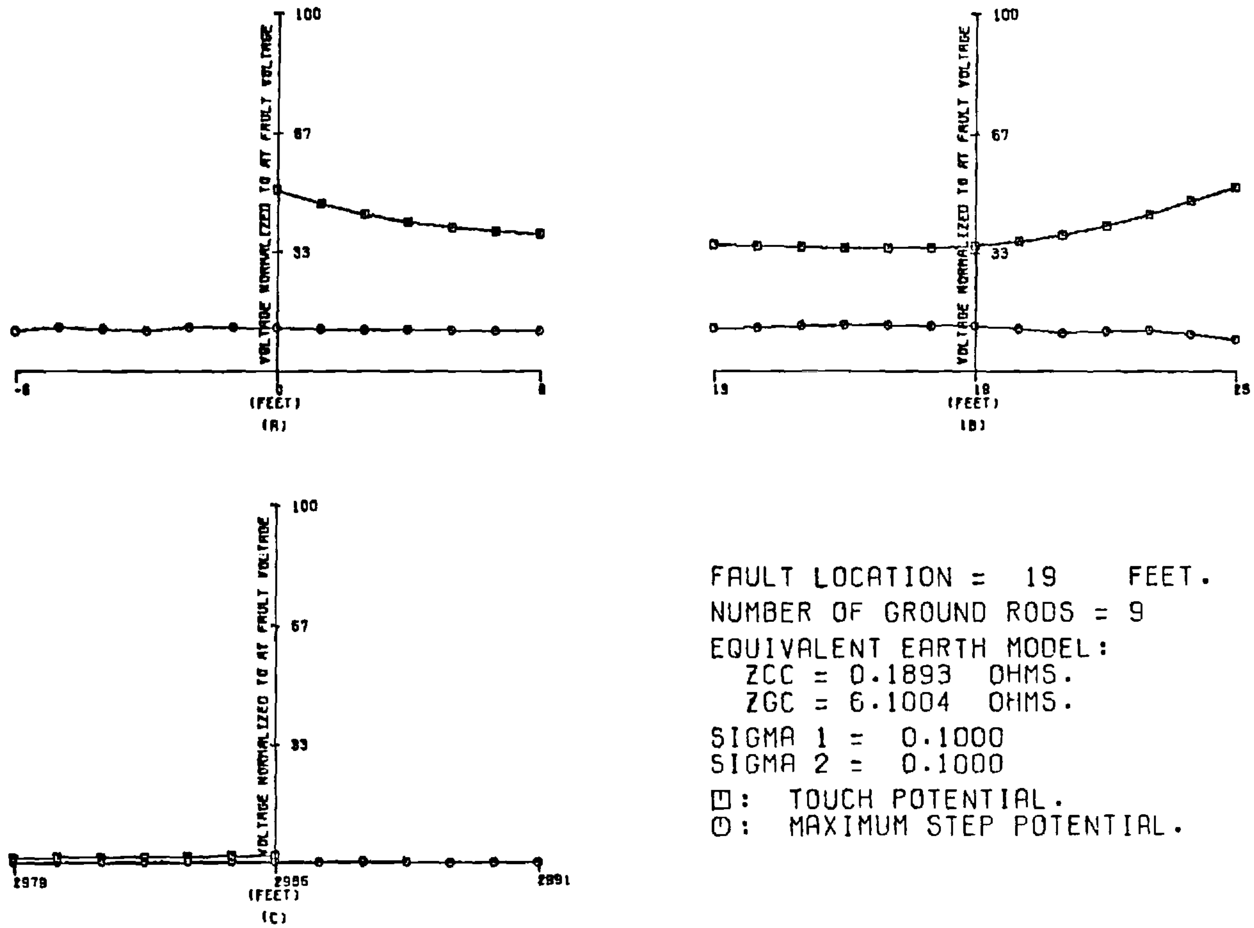


FIGURE B.2. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1893 OHMS.
ZGC = 6.1004 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.3. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

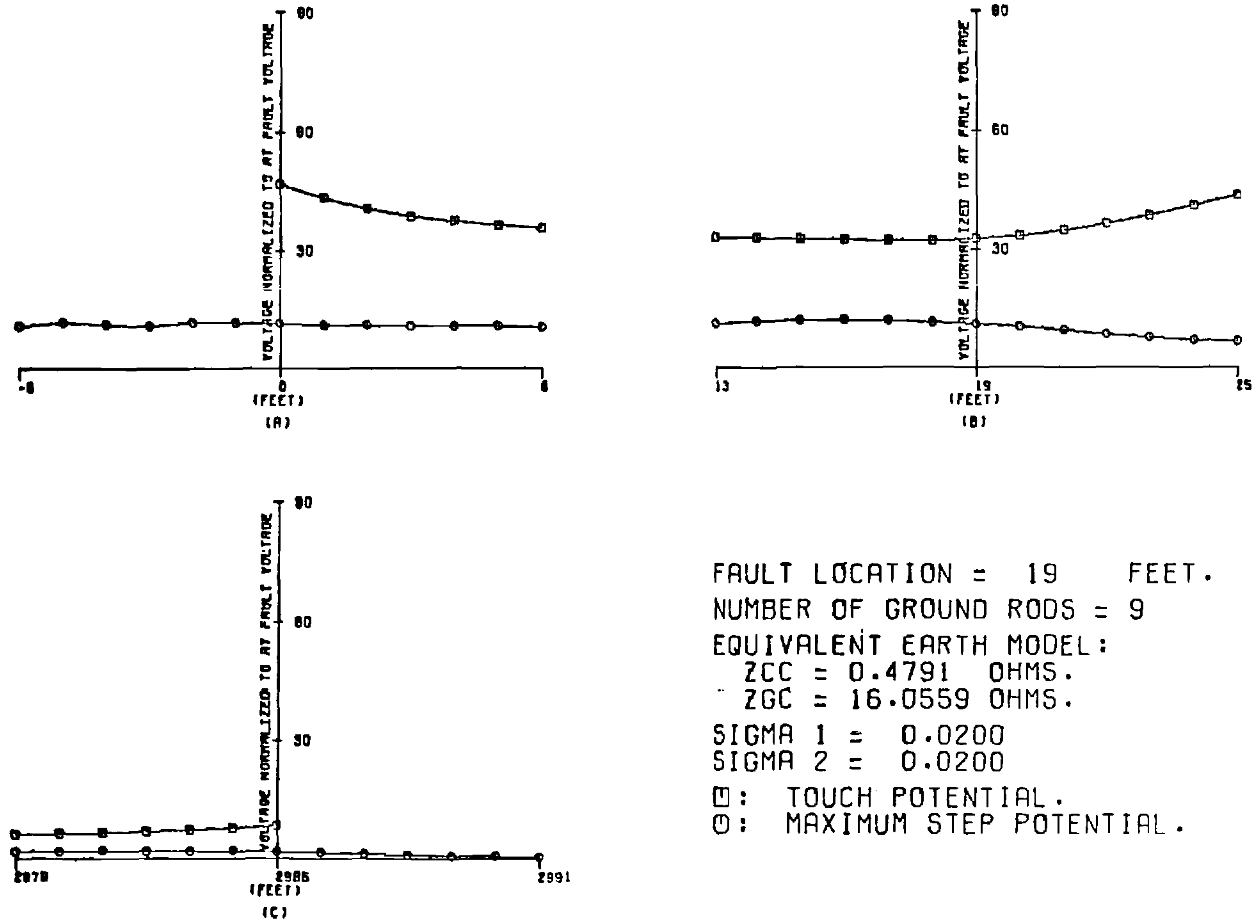


FIGURE B.4. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

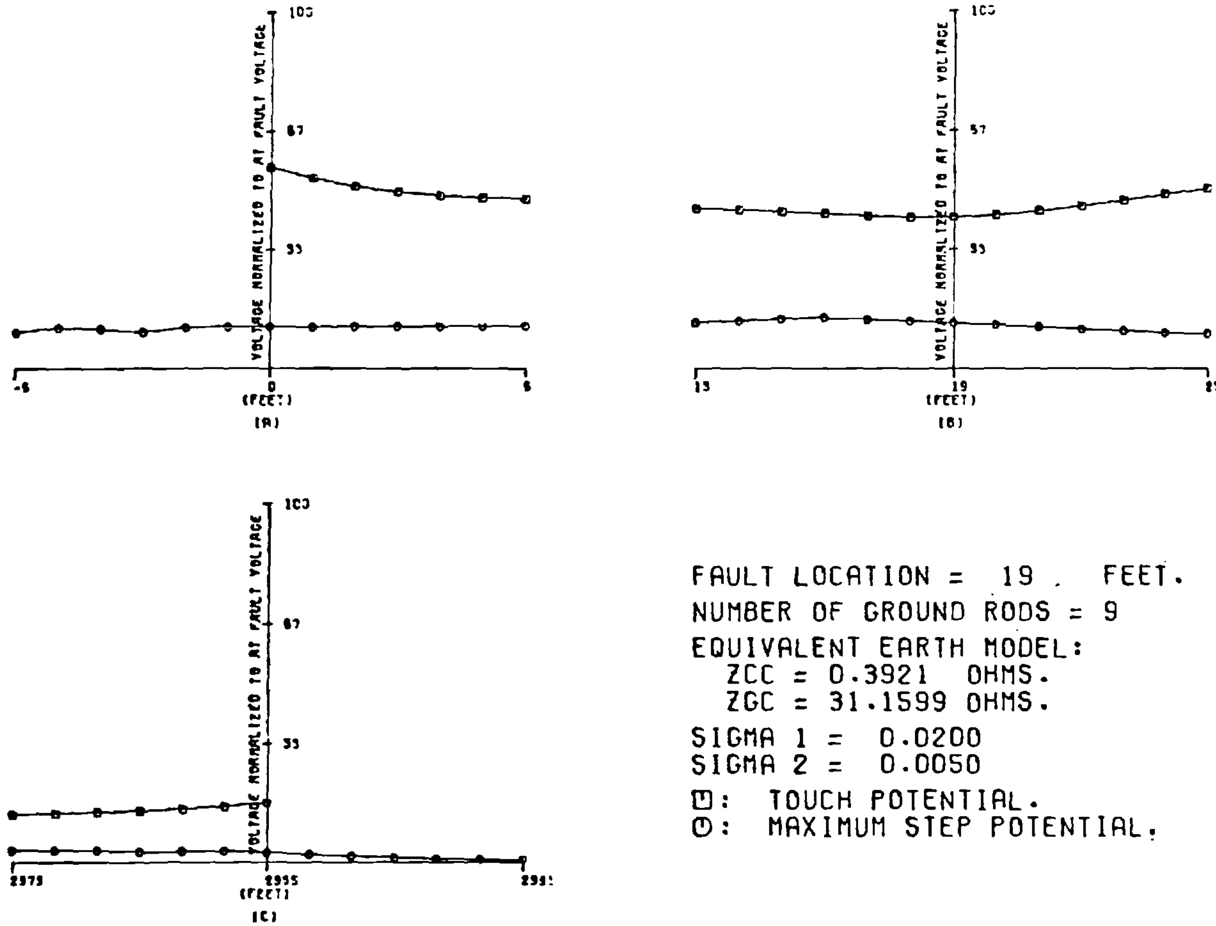


FIGURE B.5. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

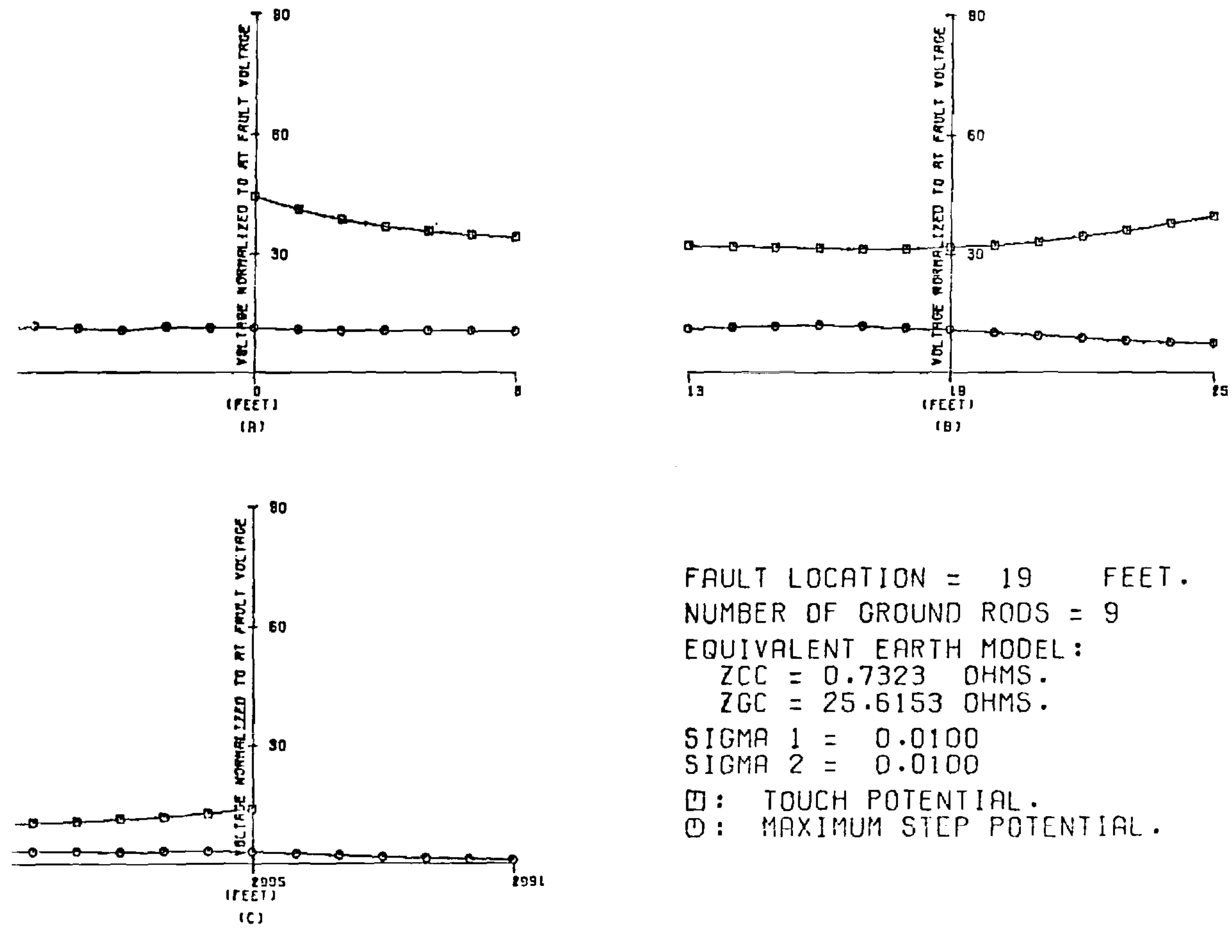


FIGURE B.6. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

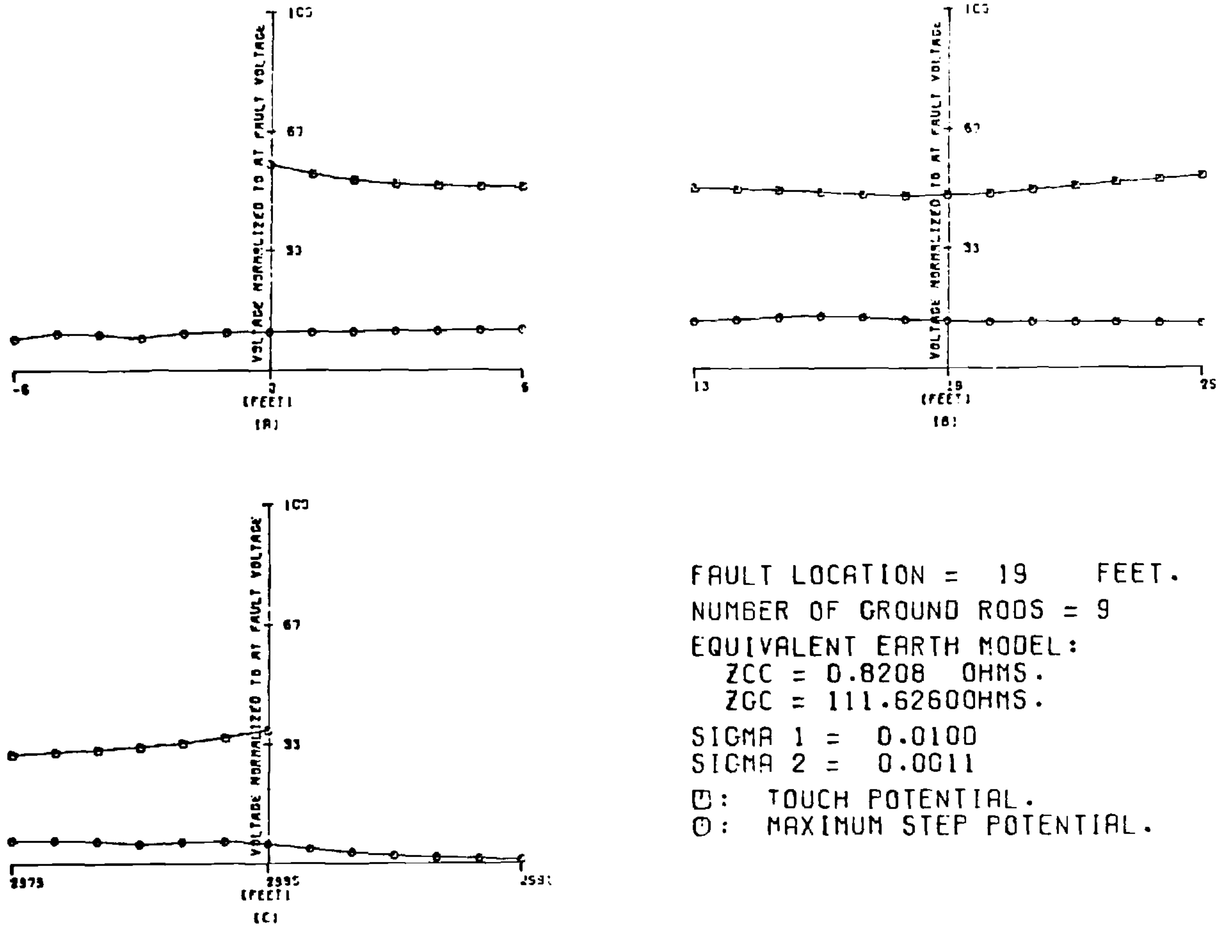


FIGURE B.7. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

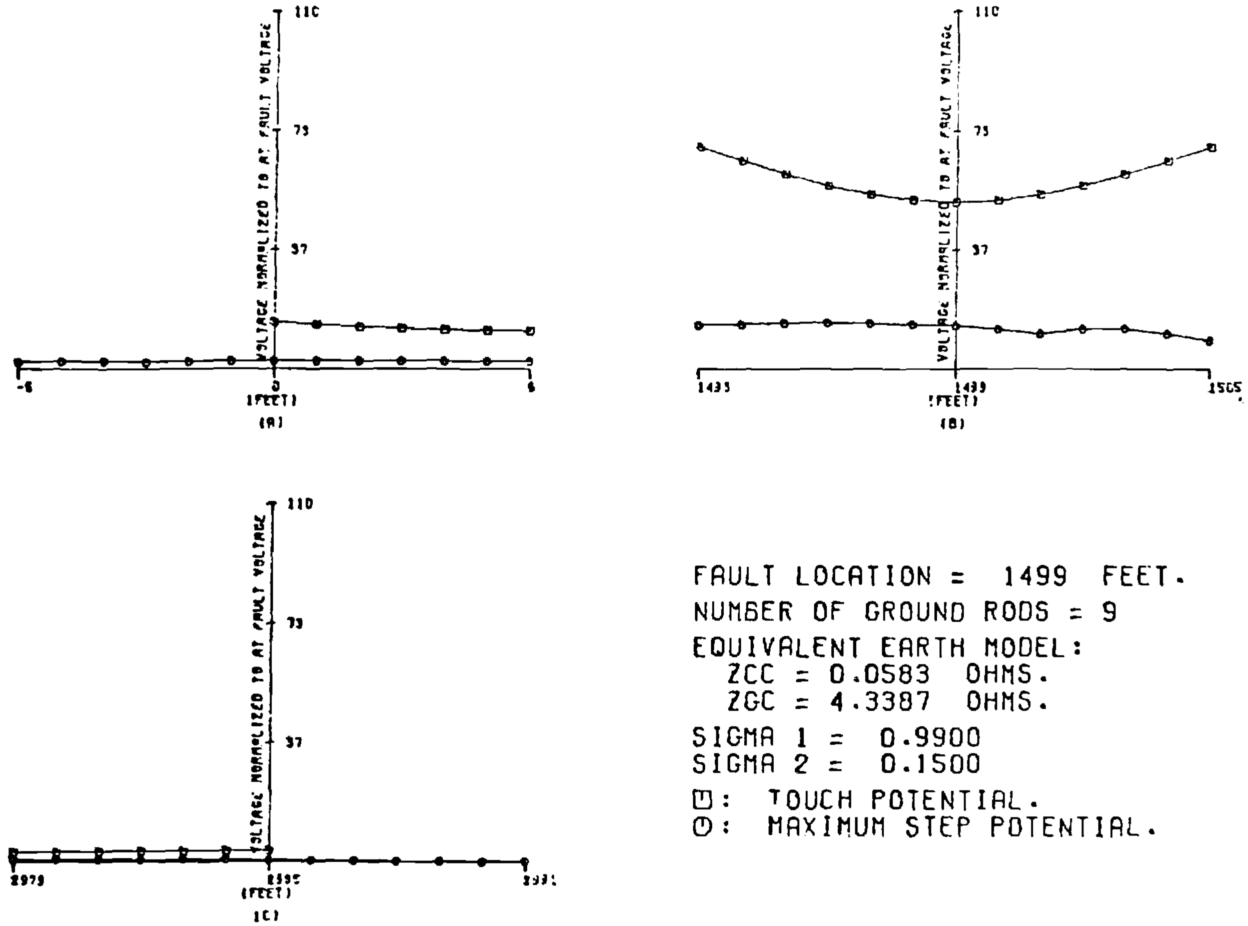


FIGURE B.8. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

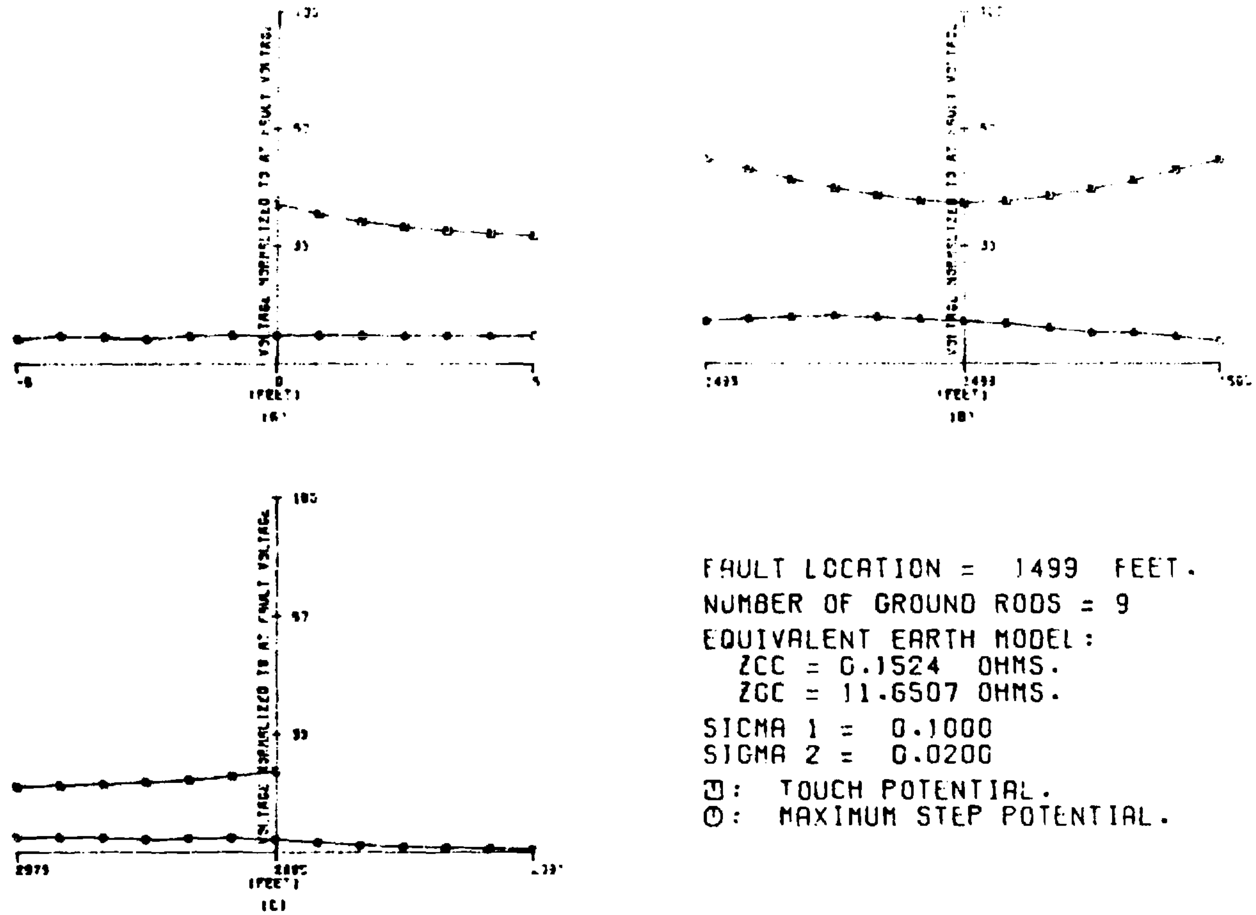


FIGURE B.9. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

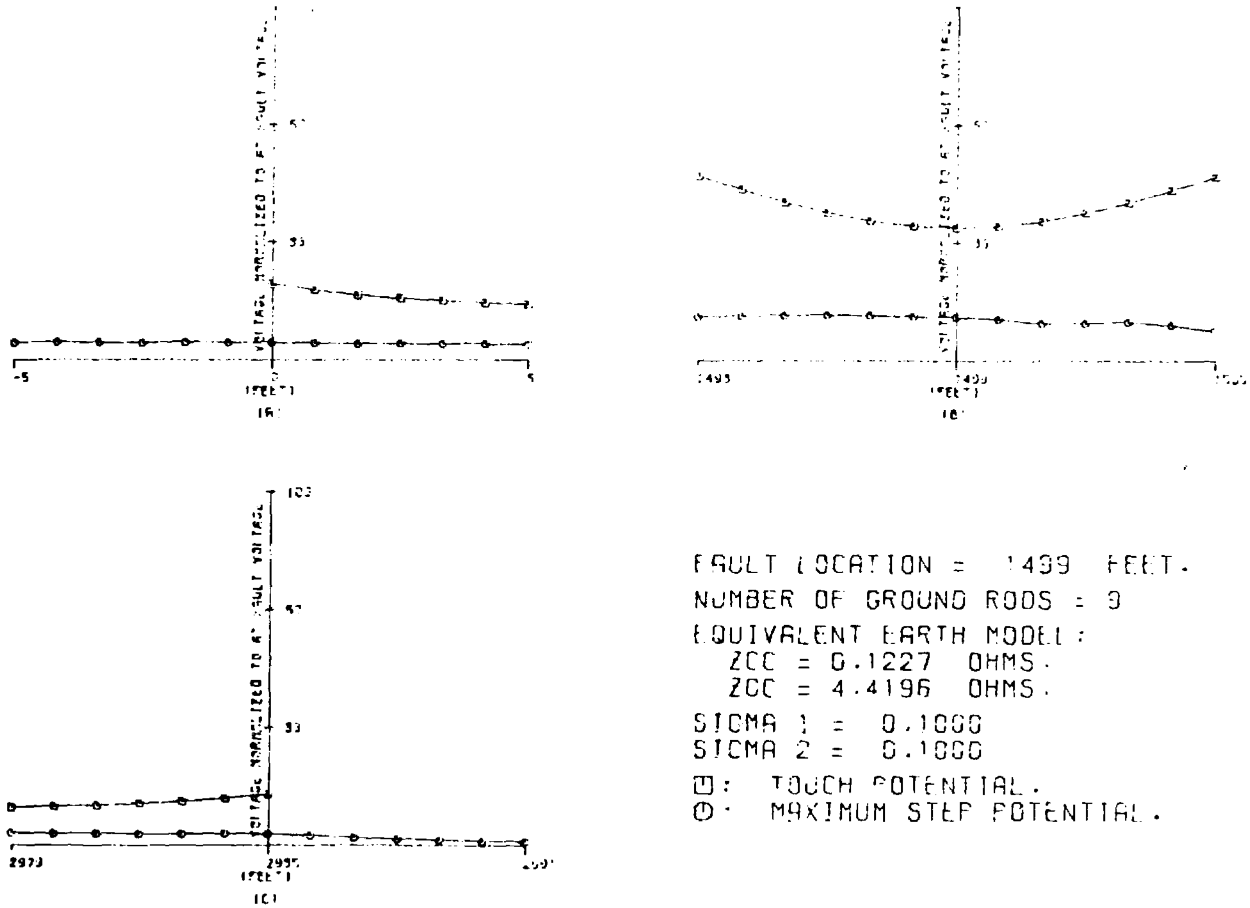


FIGURE B.10. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

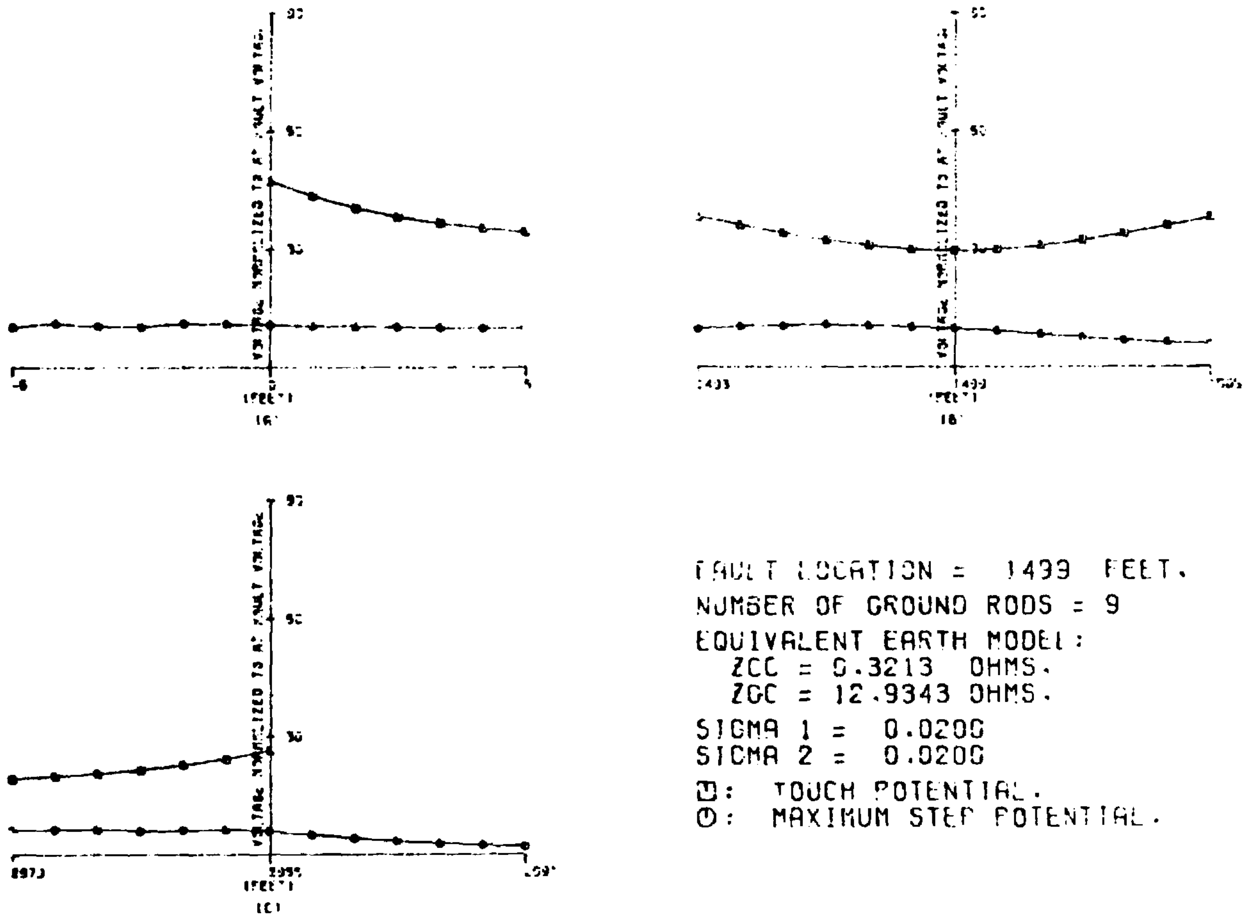


FIGURE B.11. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

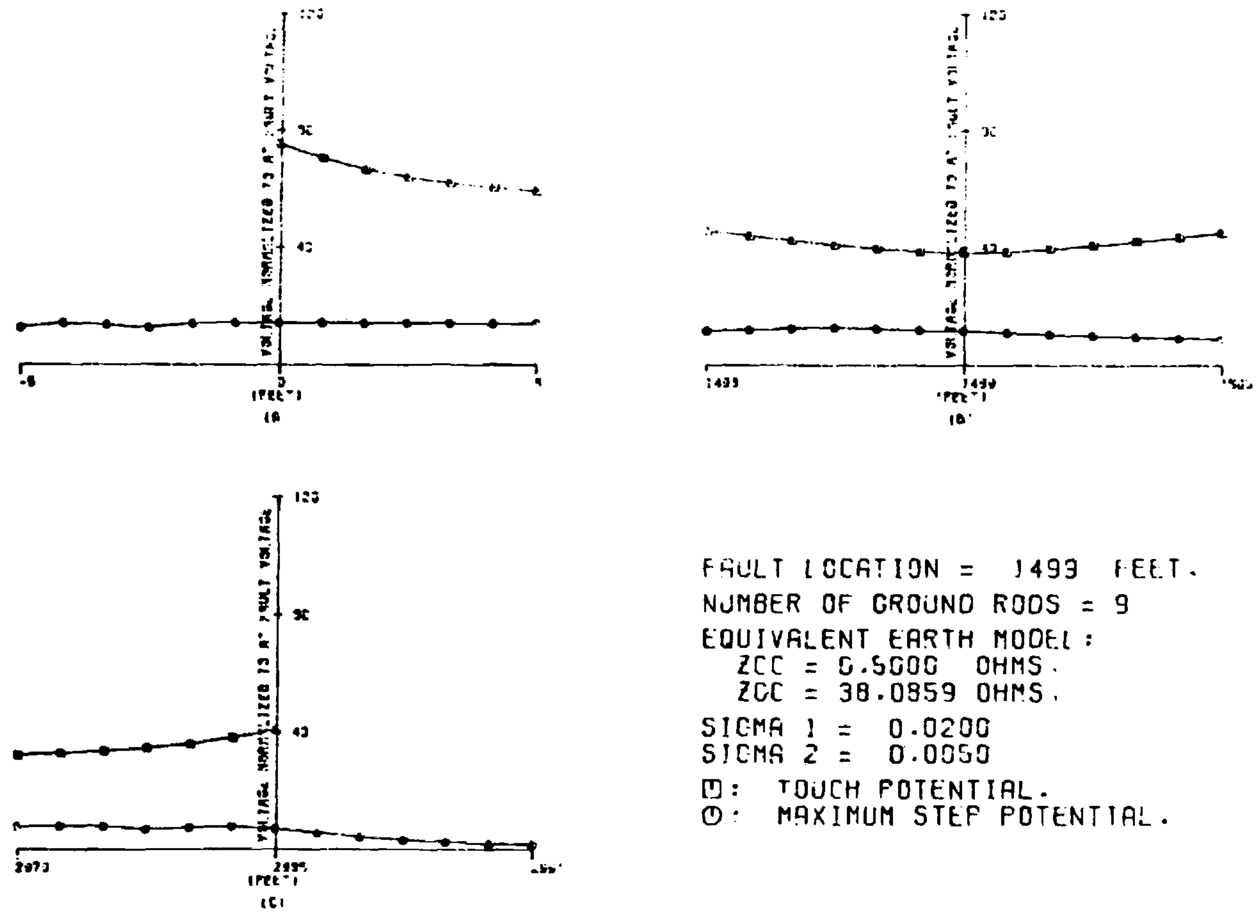
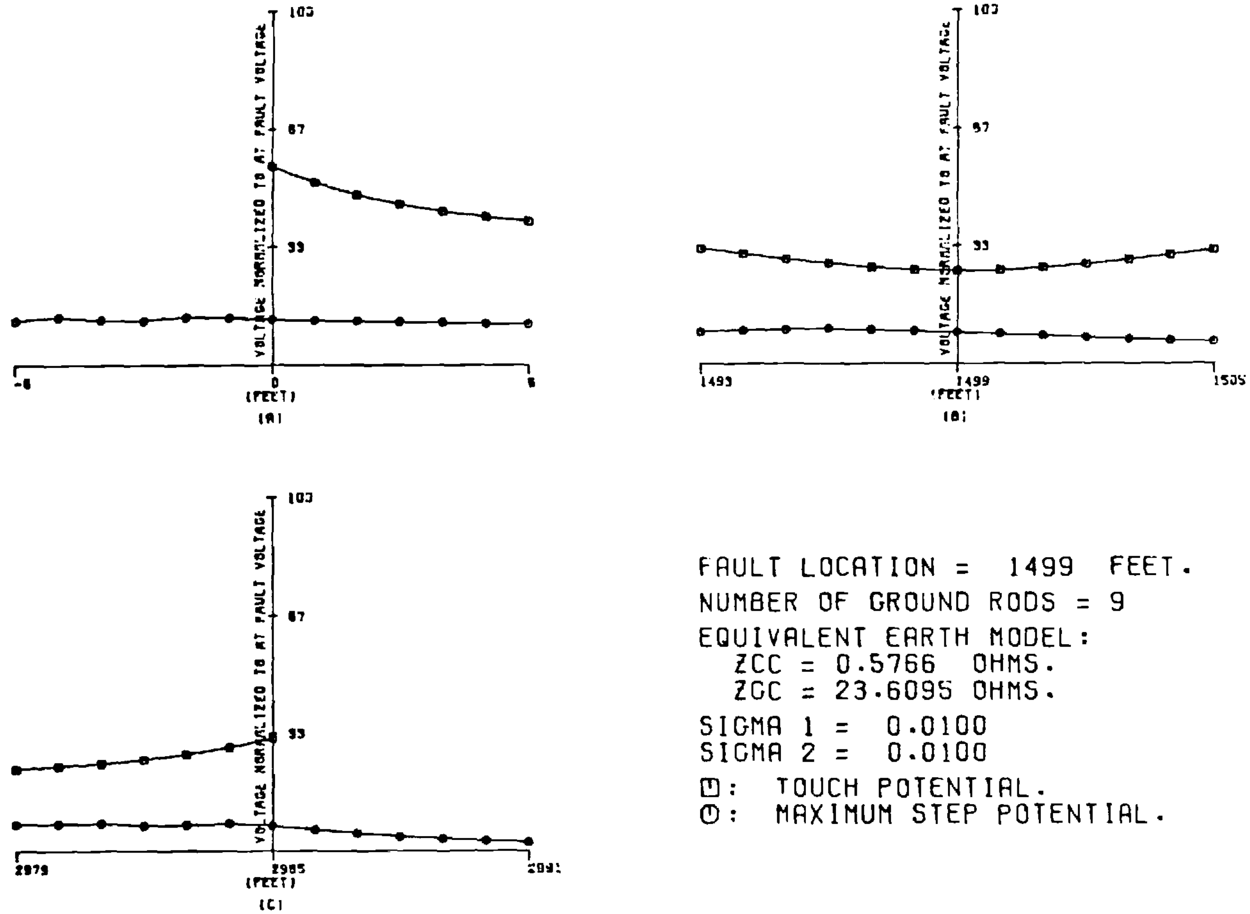


FIGURE B.12. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.5766 OHMS.
ZCC = 23.6095 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.13. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

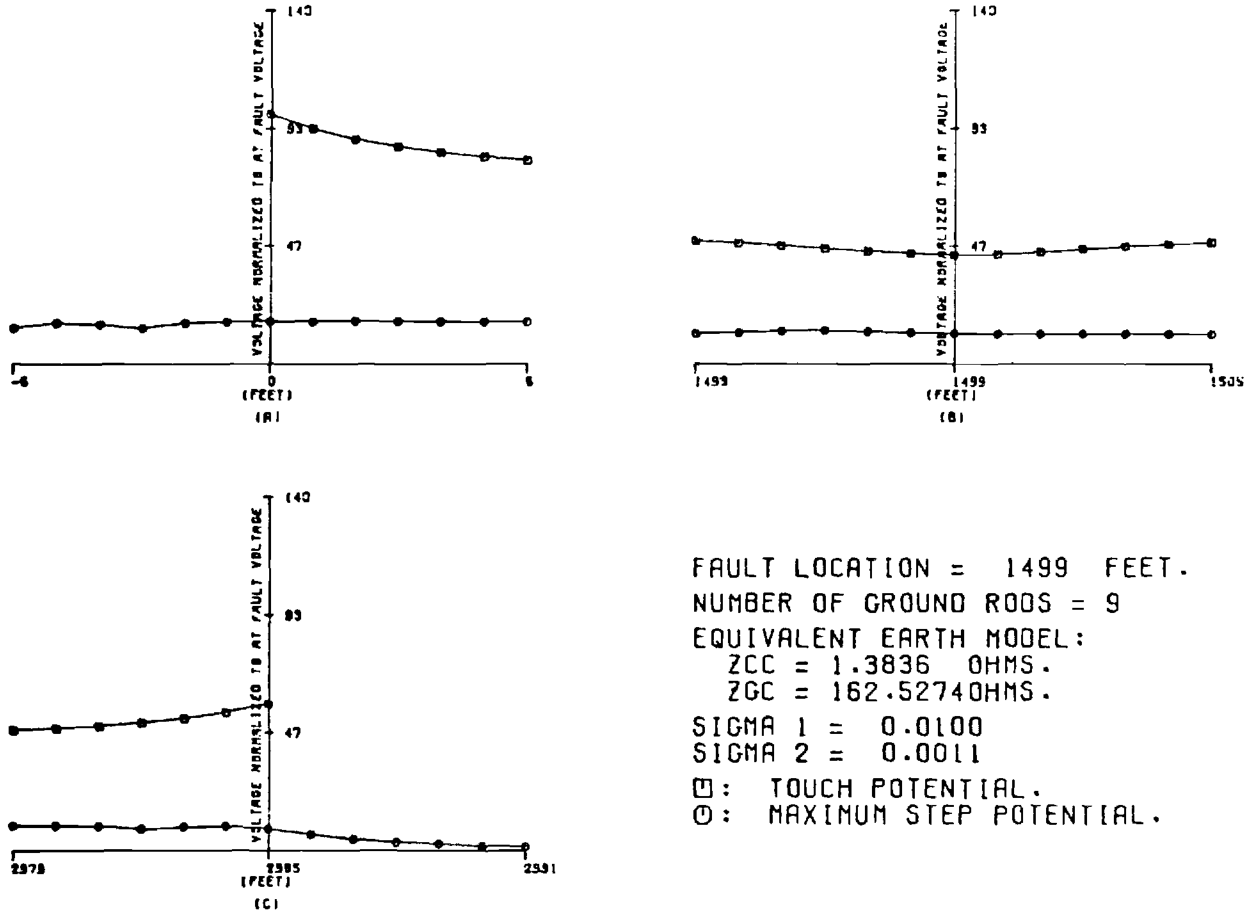


FIGURE B.14. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

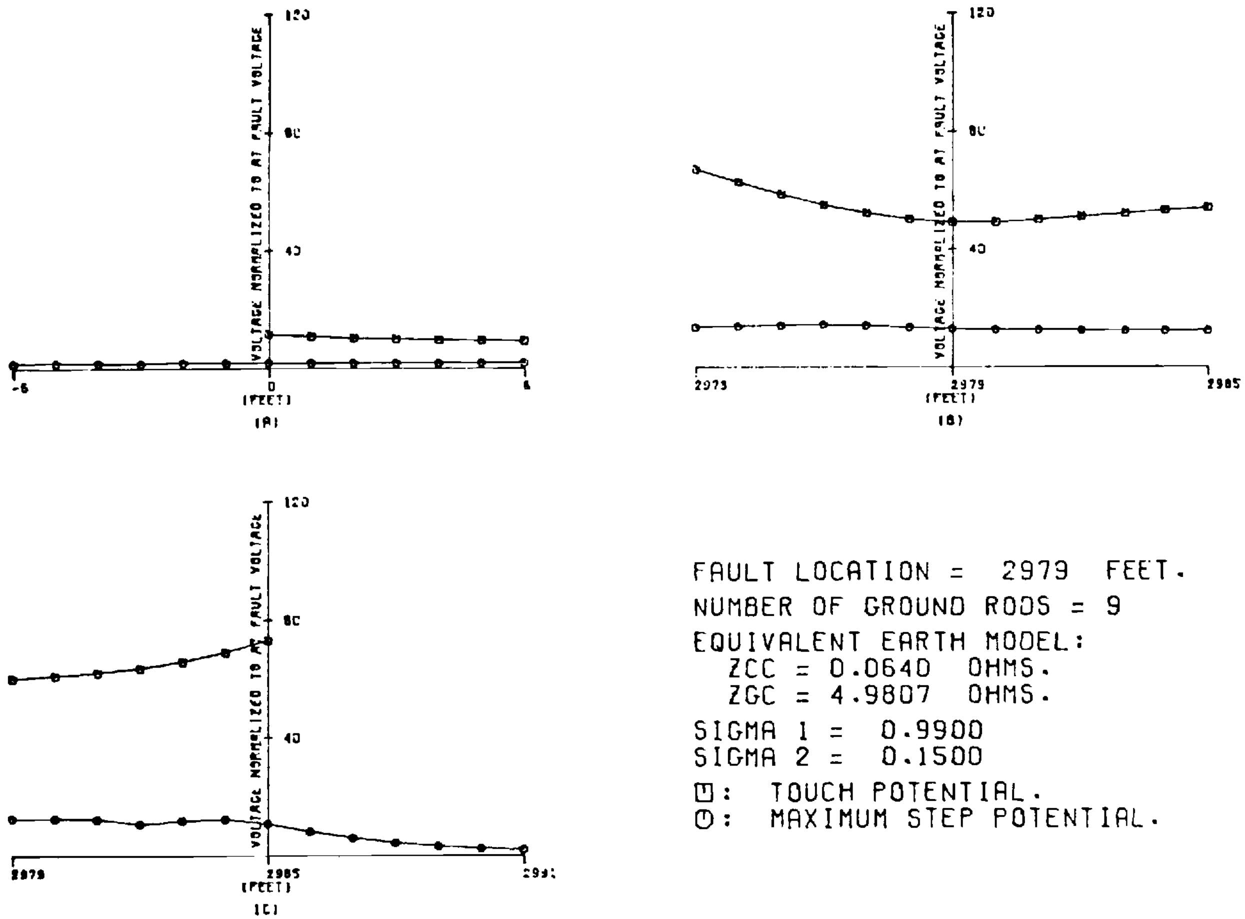


FIGURE B.15. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

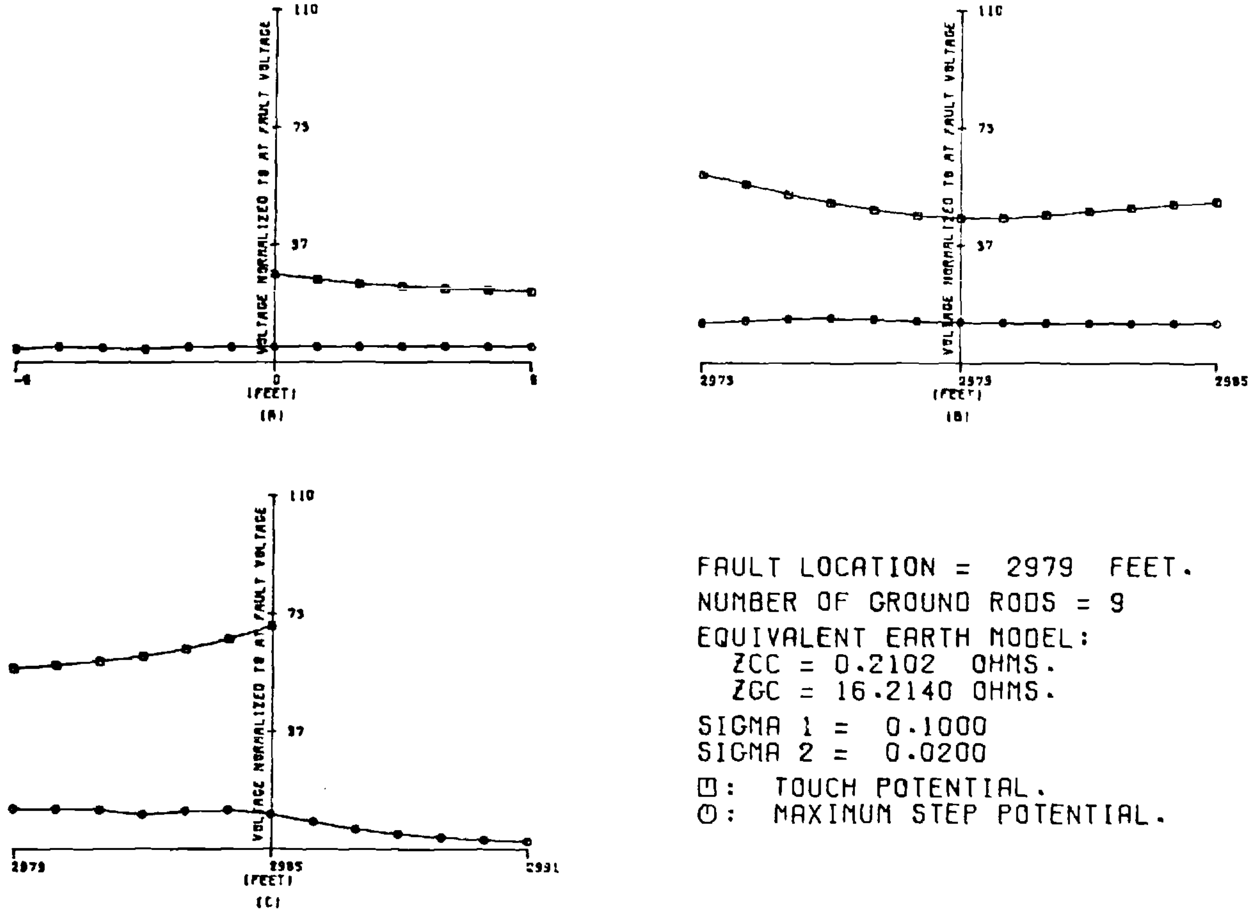


FIGURE B.16. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

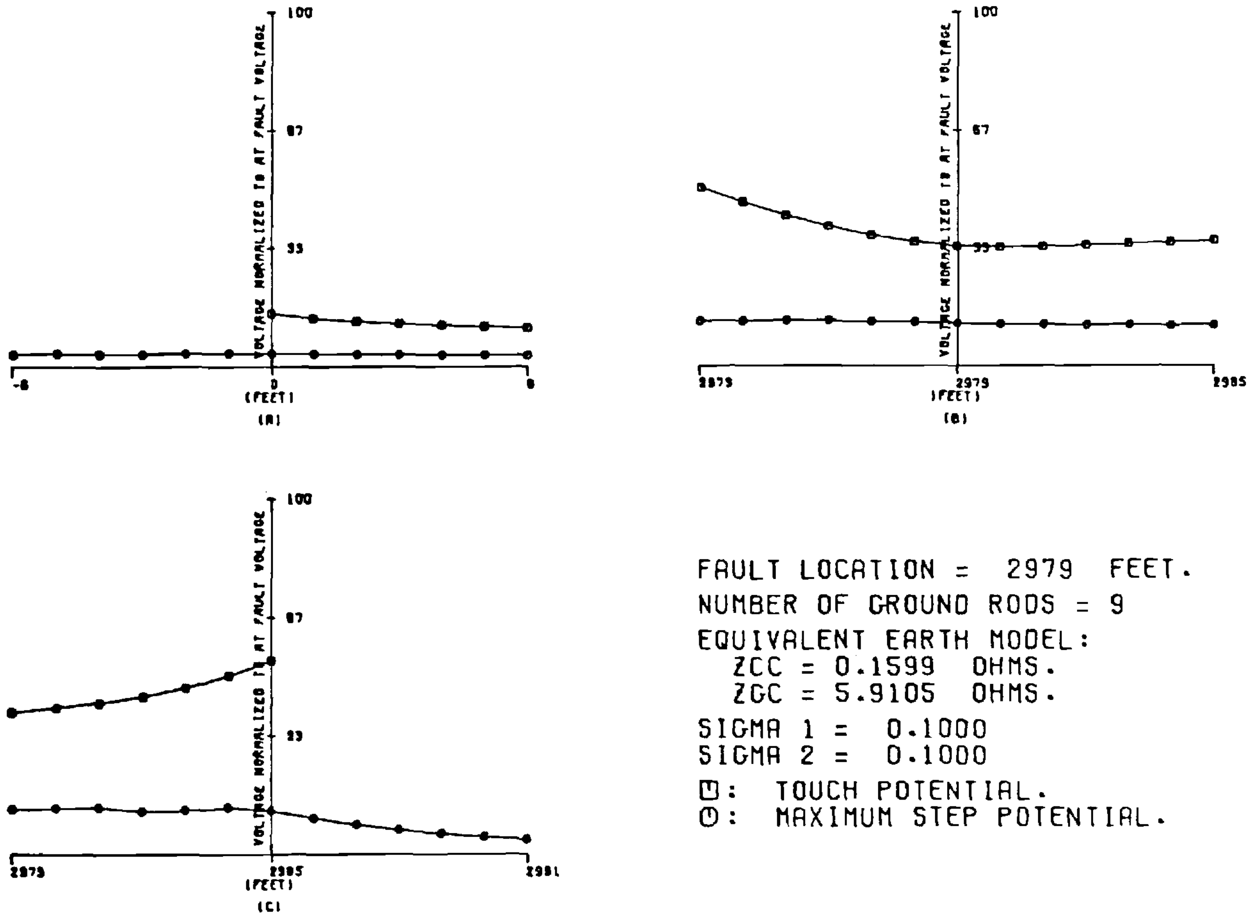


FIGURE 3.17. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

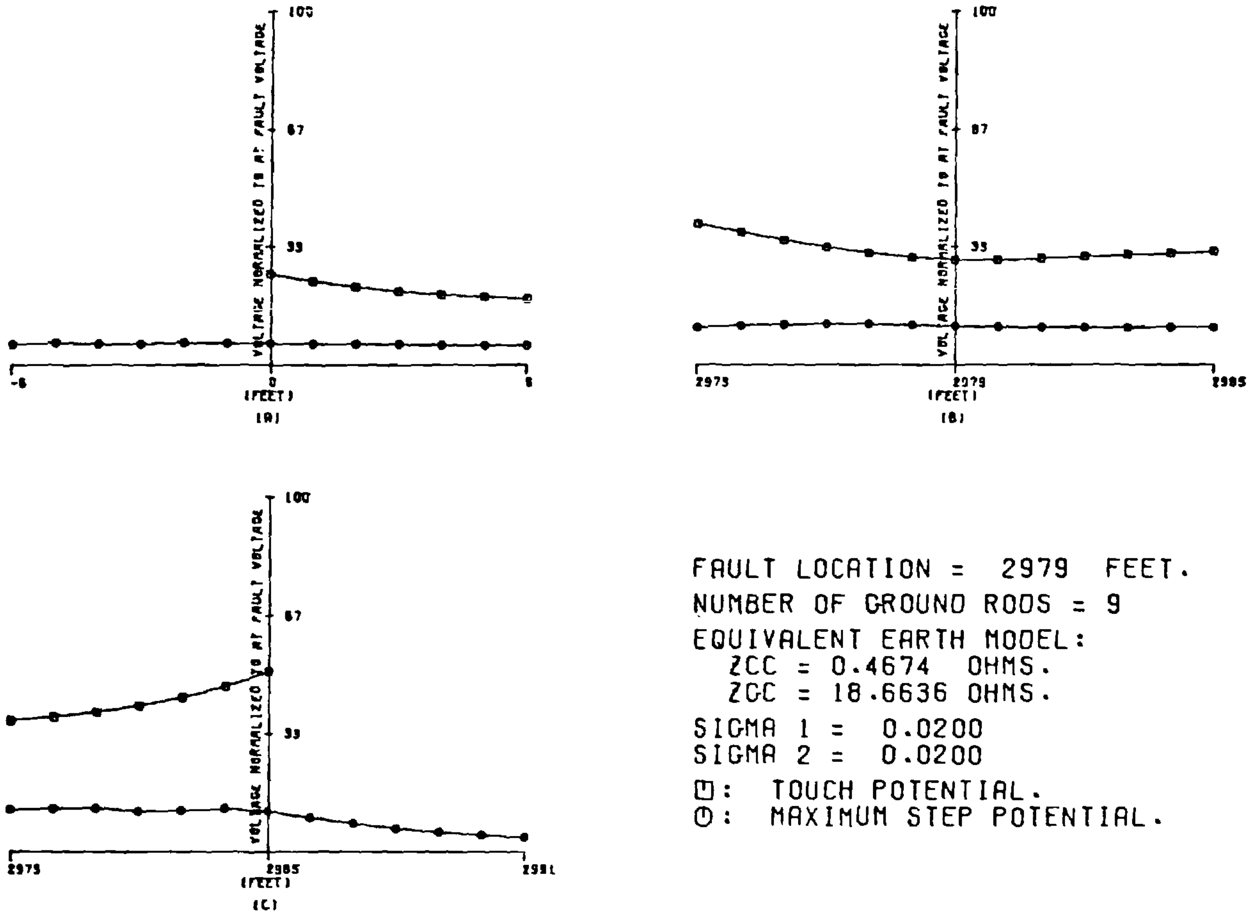


FIGURE B.18. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

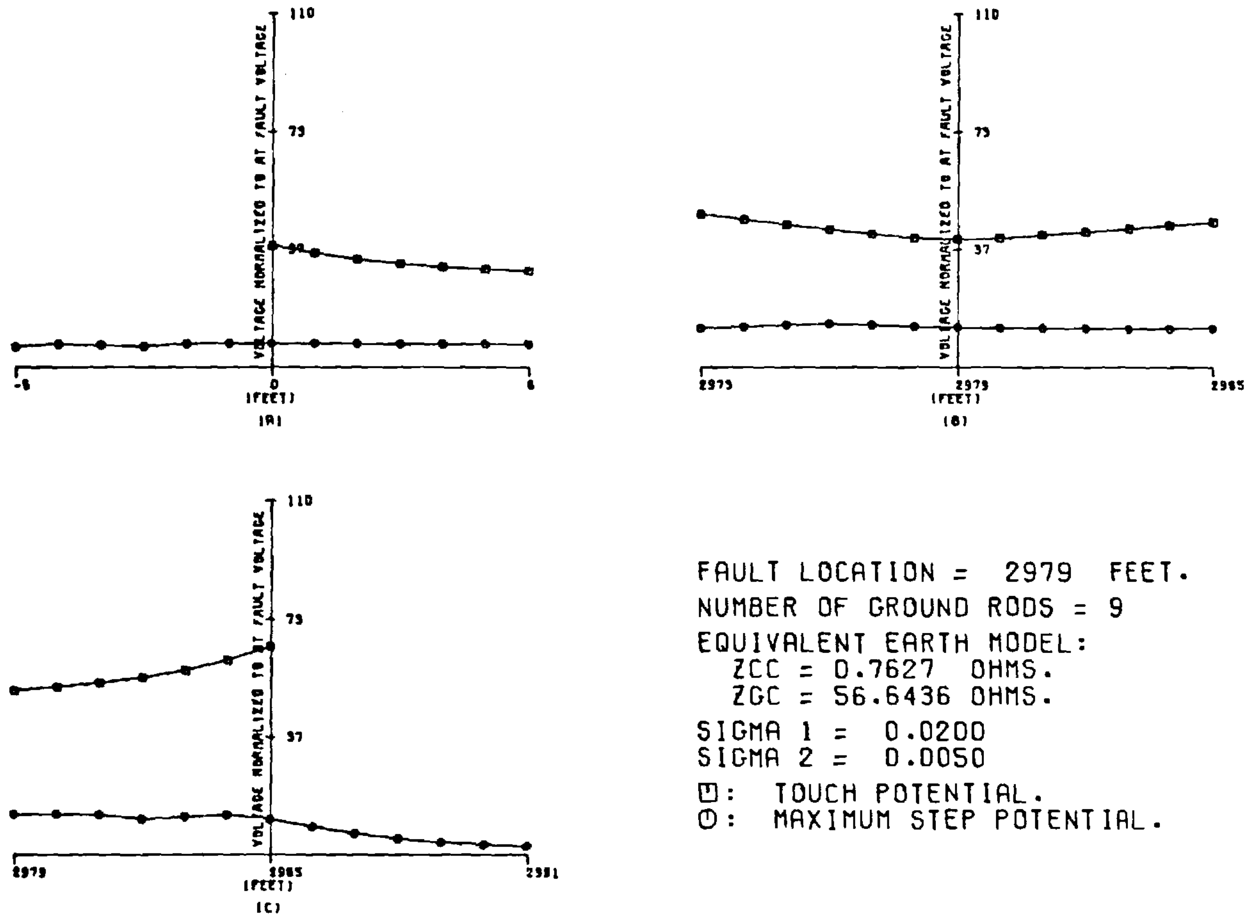
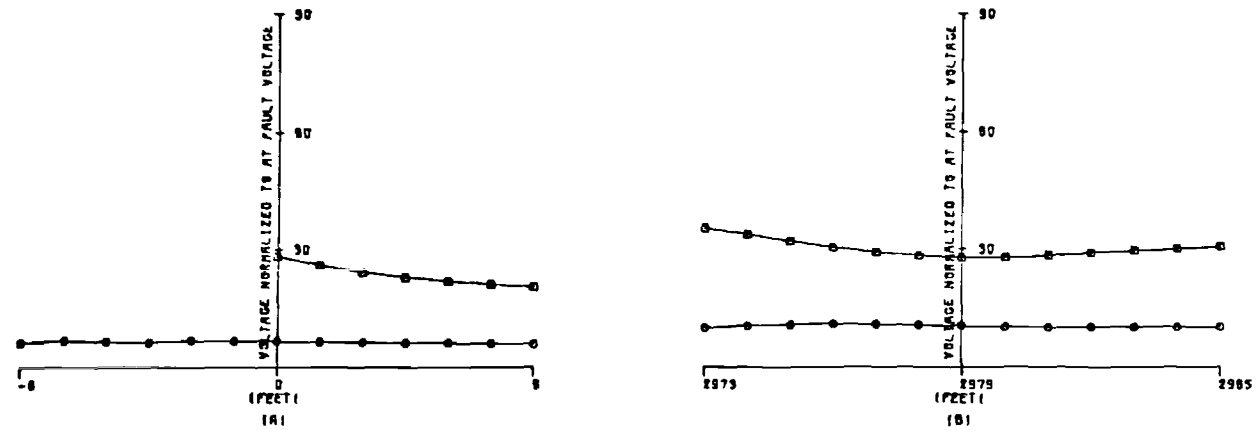
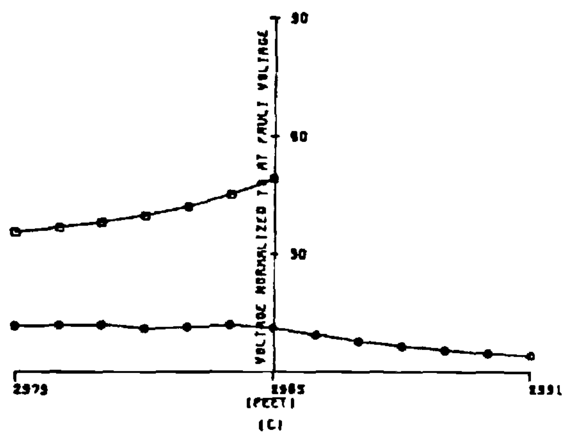


FIGURE B.19. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.8765 OHMS.
ZGC = 35.0945 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.20. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

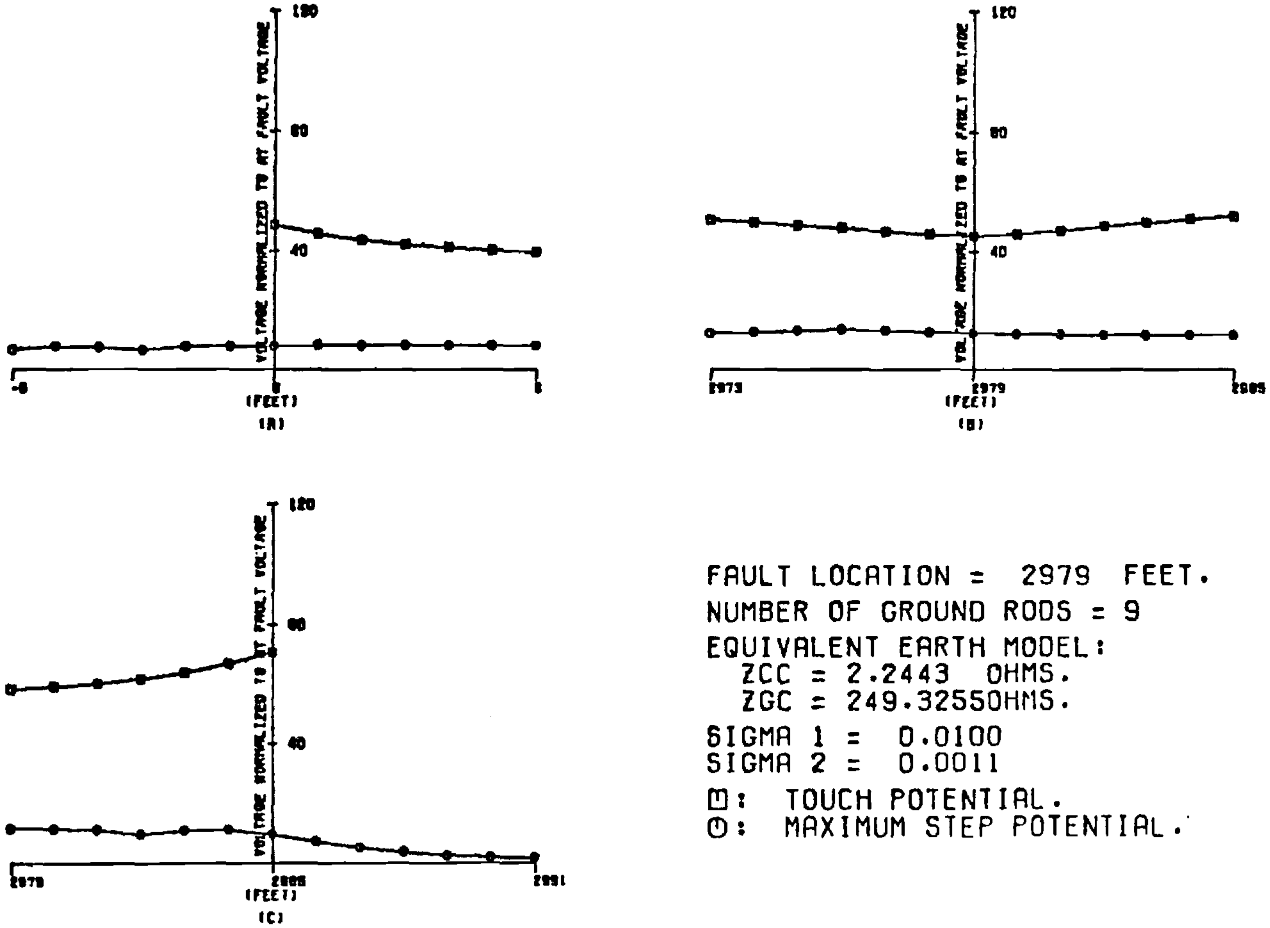


FIGURE B.21. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

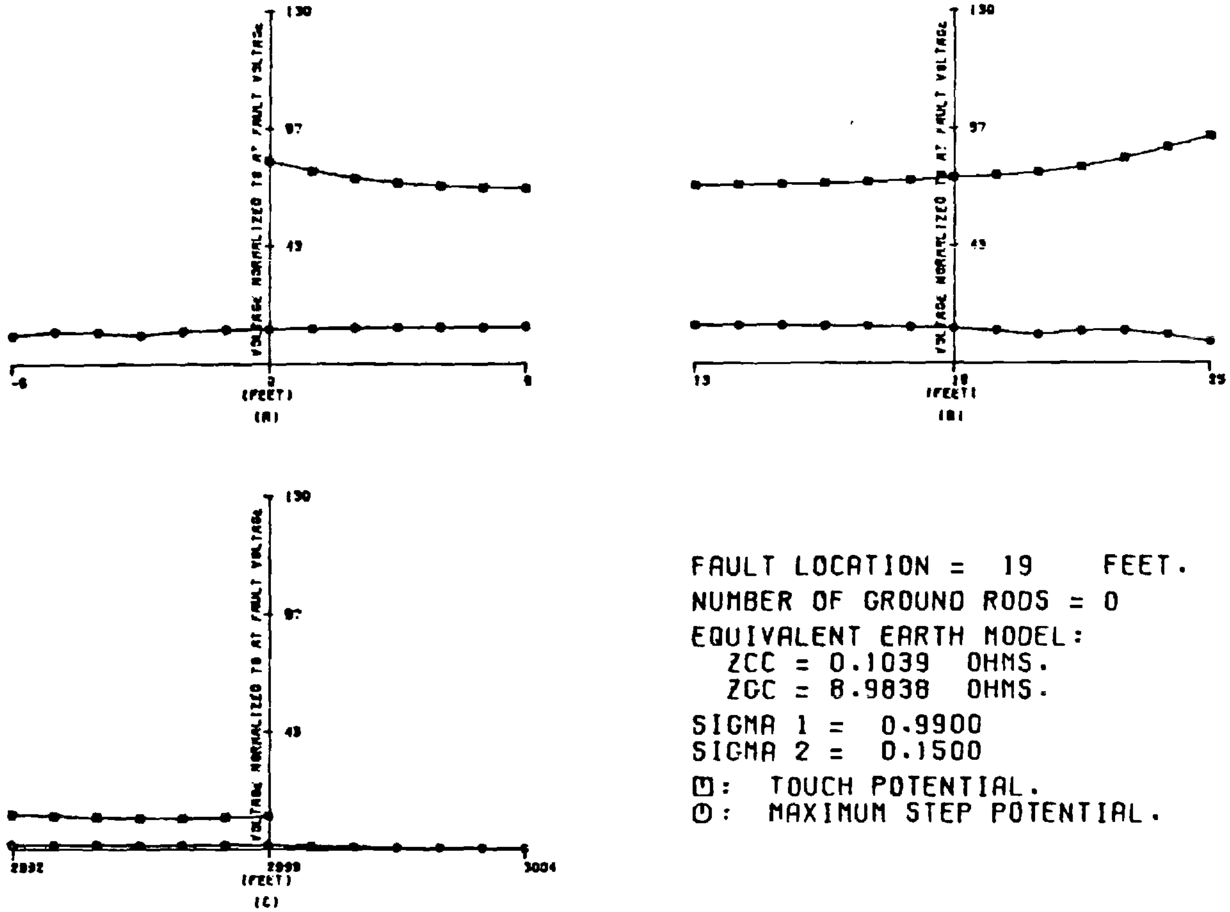


FIGURE B.22. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

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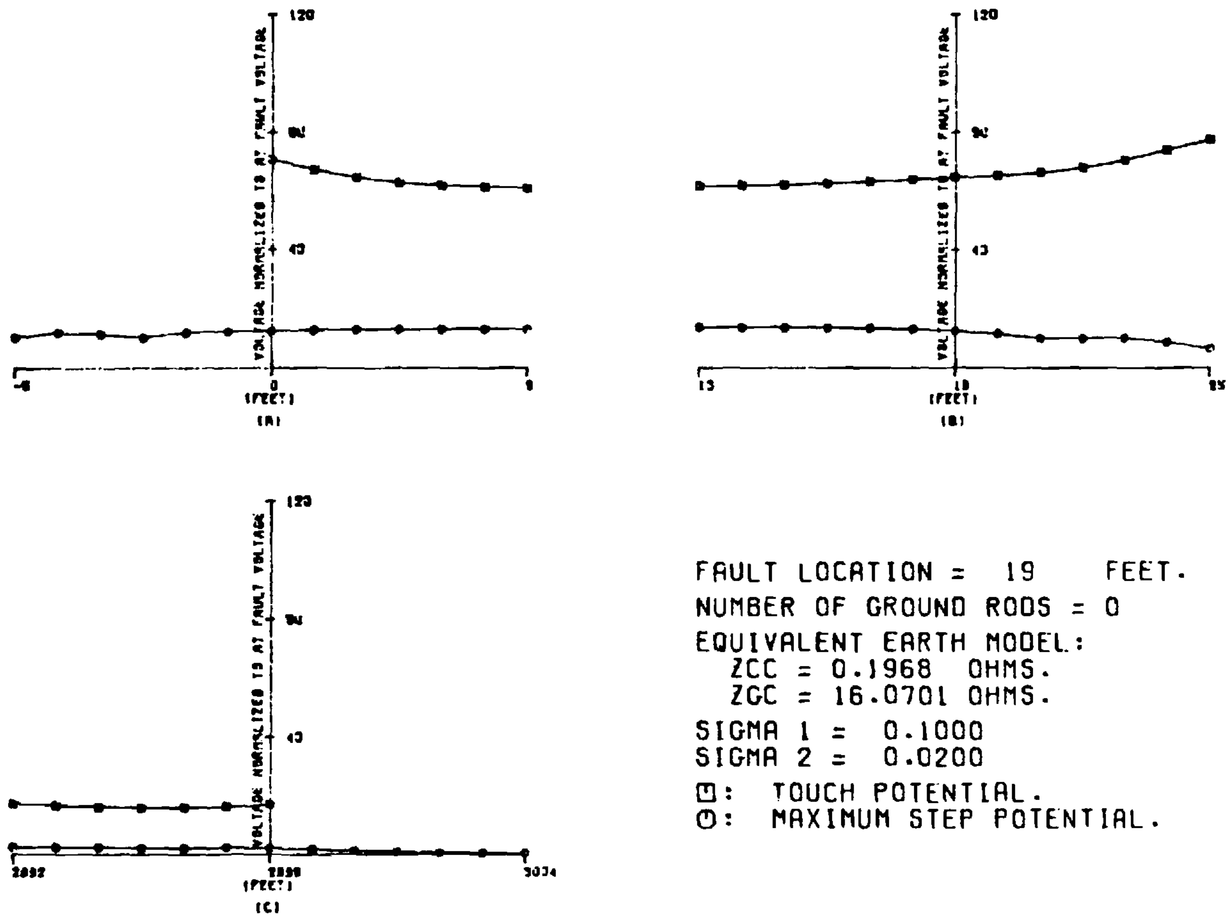
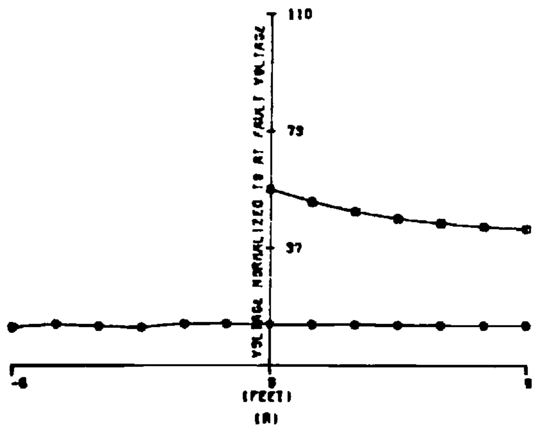
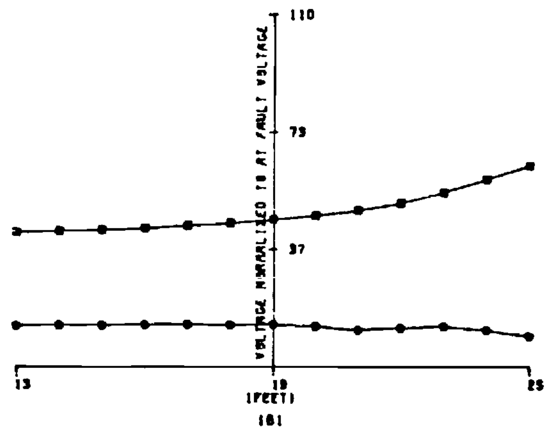
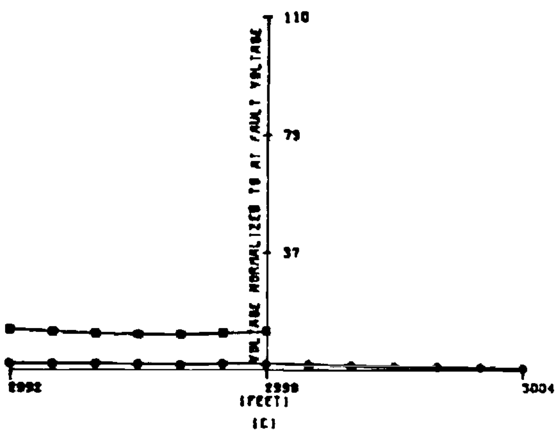


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1968 OHMS.
ZGC = 16.0701 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.23. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1474 OHMS.
ZGC = 5.7884 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.24. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

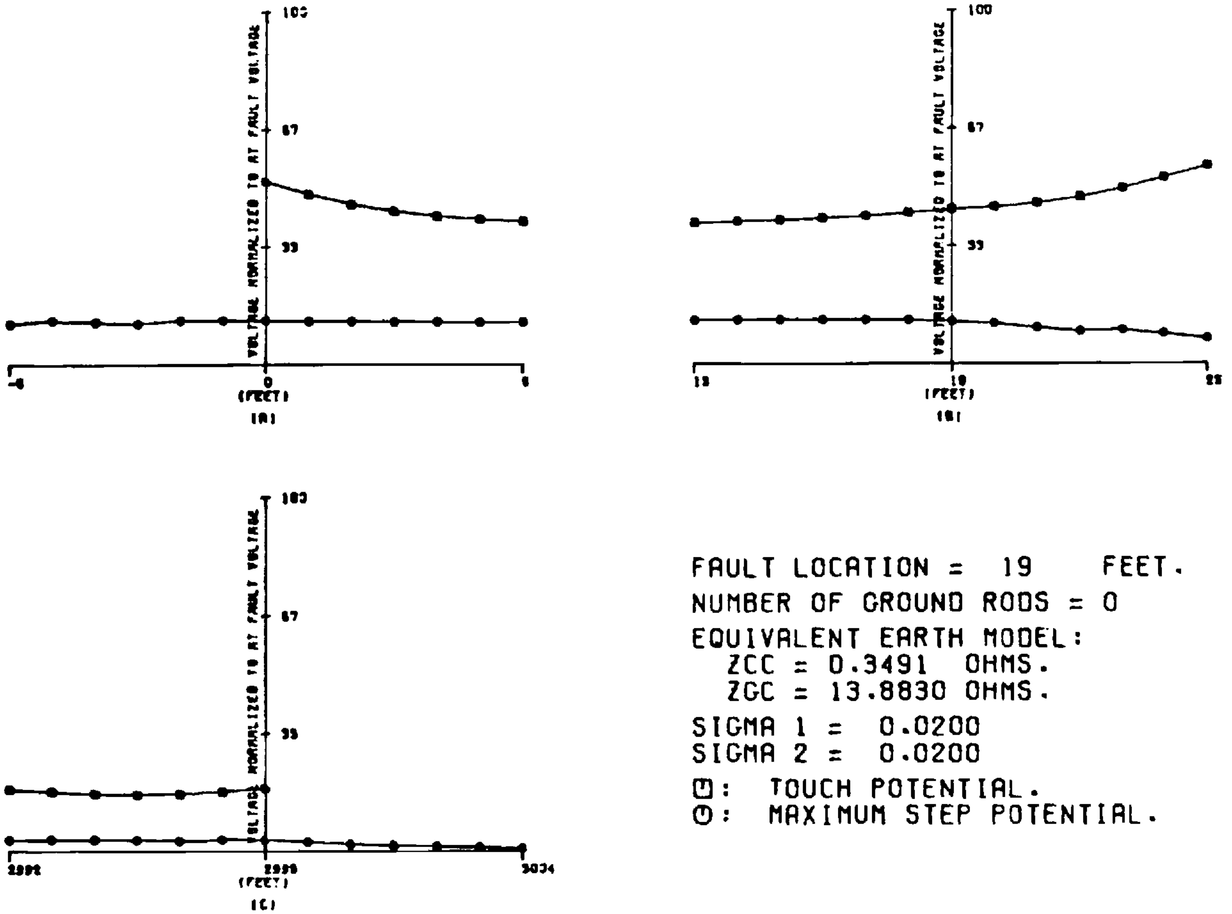
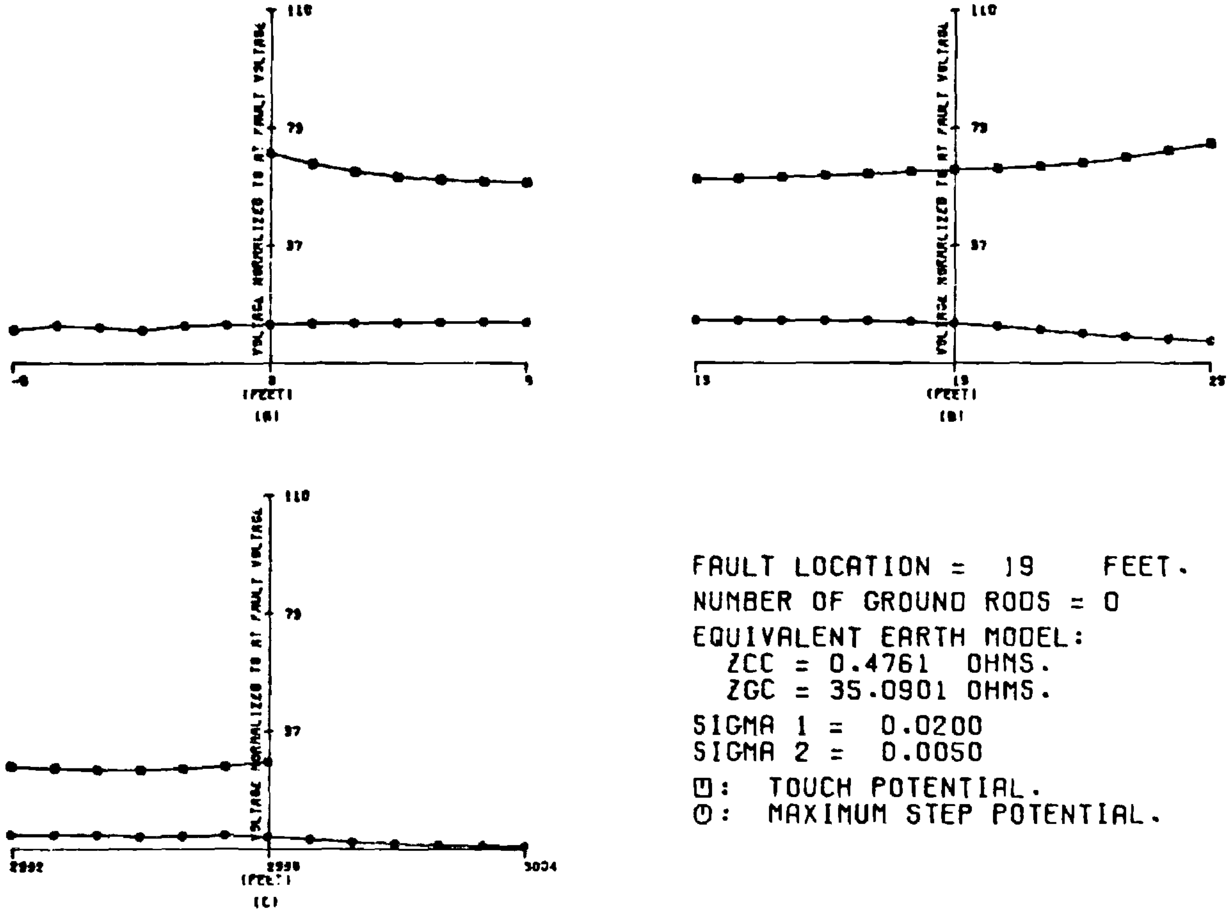
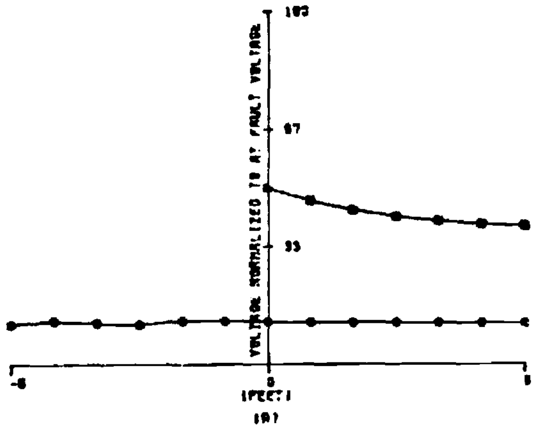


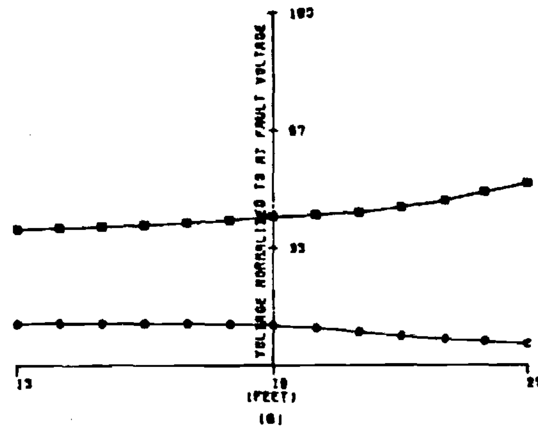
FIGURE B.25. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

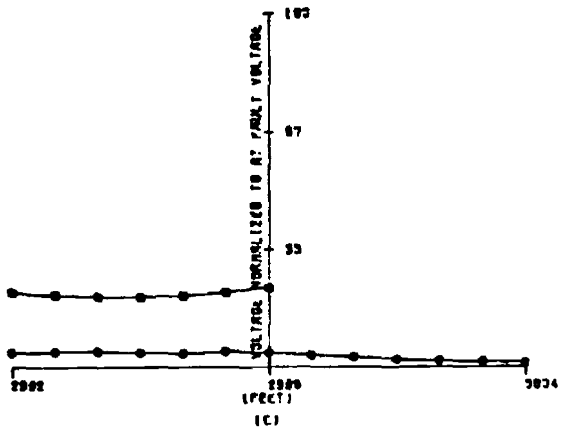


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.4761 OHMS.
ZGC = 35.0901 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
☐: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.26. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

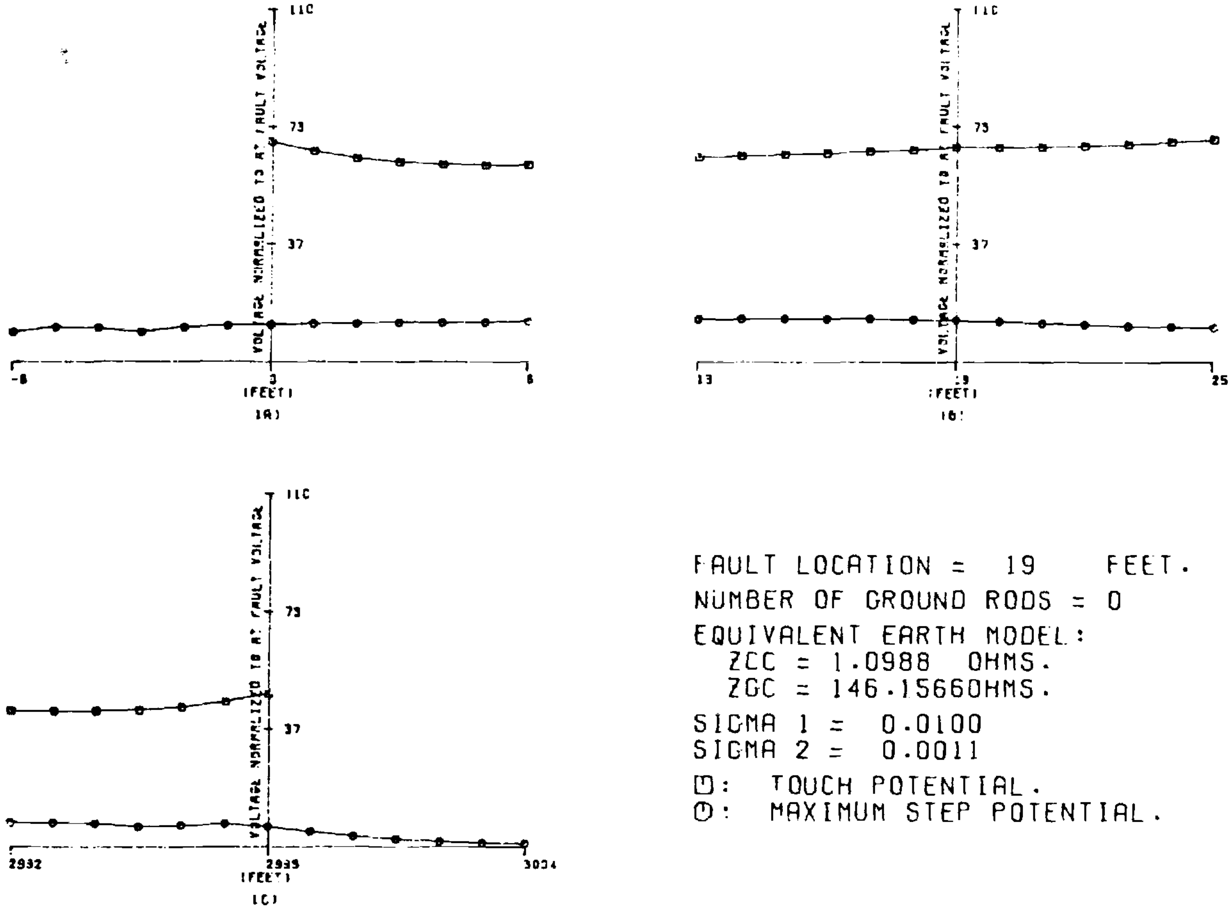






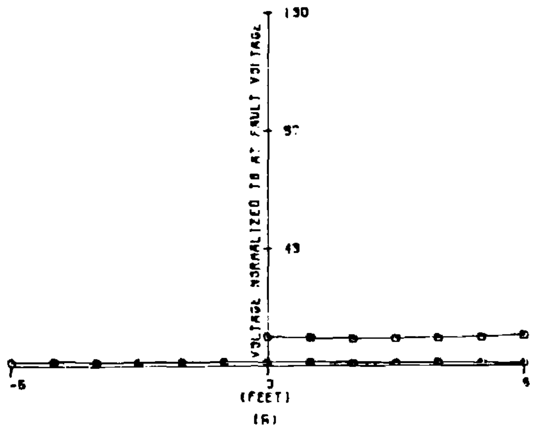
FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5336 OHMS.
ZGC = 21.9993 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

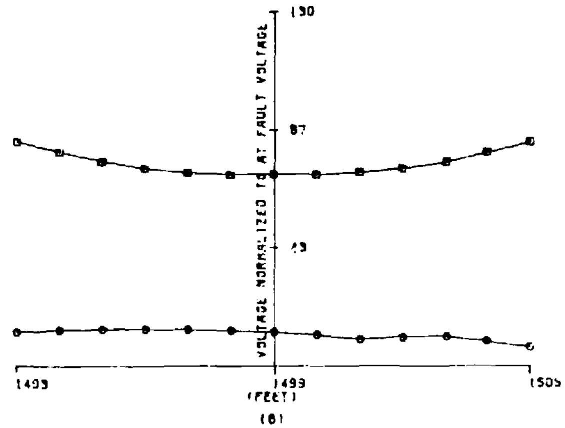
FIGURE B.27. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

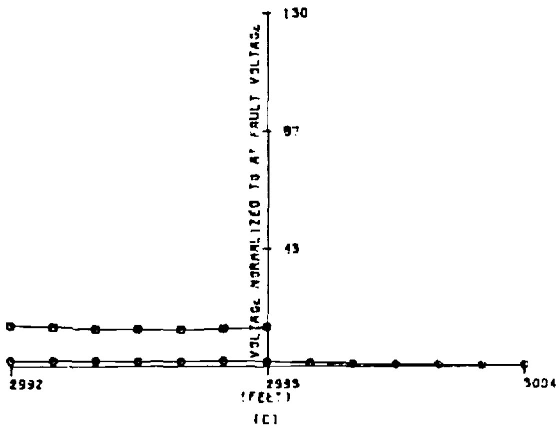


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 1.0988 OHMS.
ZGC = 146.1566OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.23. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.0804 OHMS.
ZGC = 6.1680 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.29. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

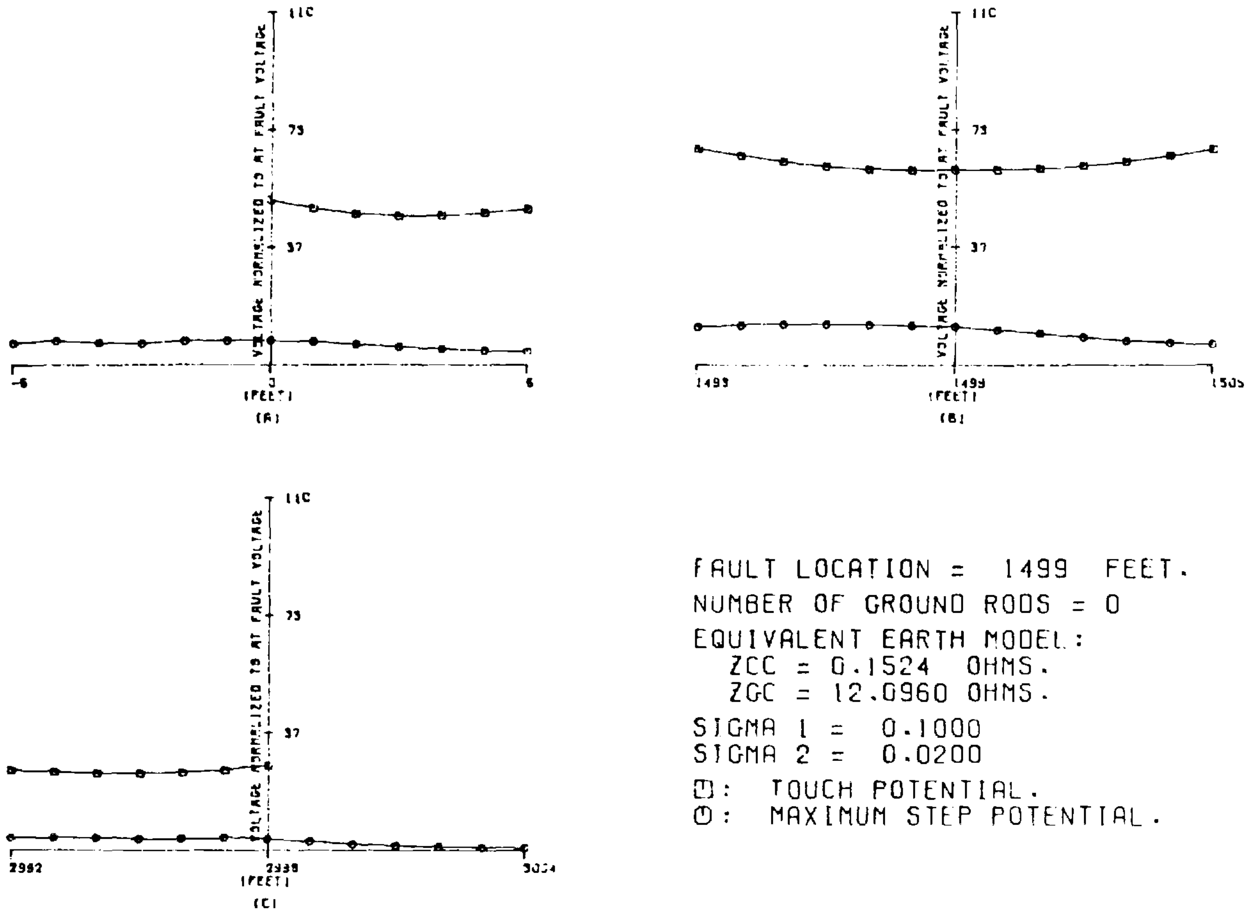
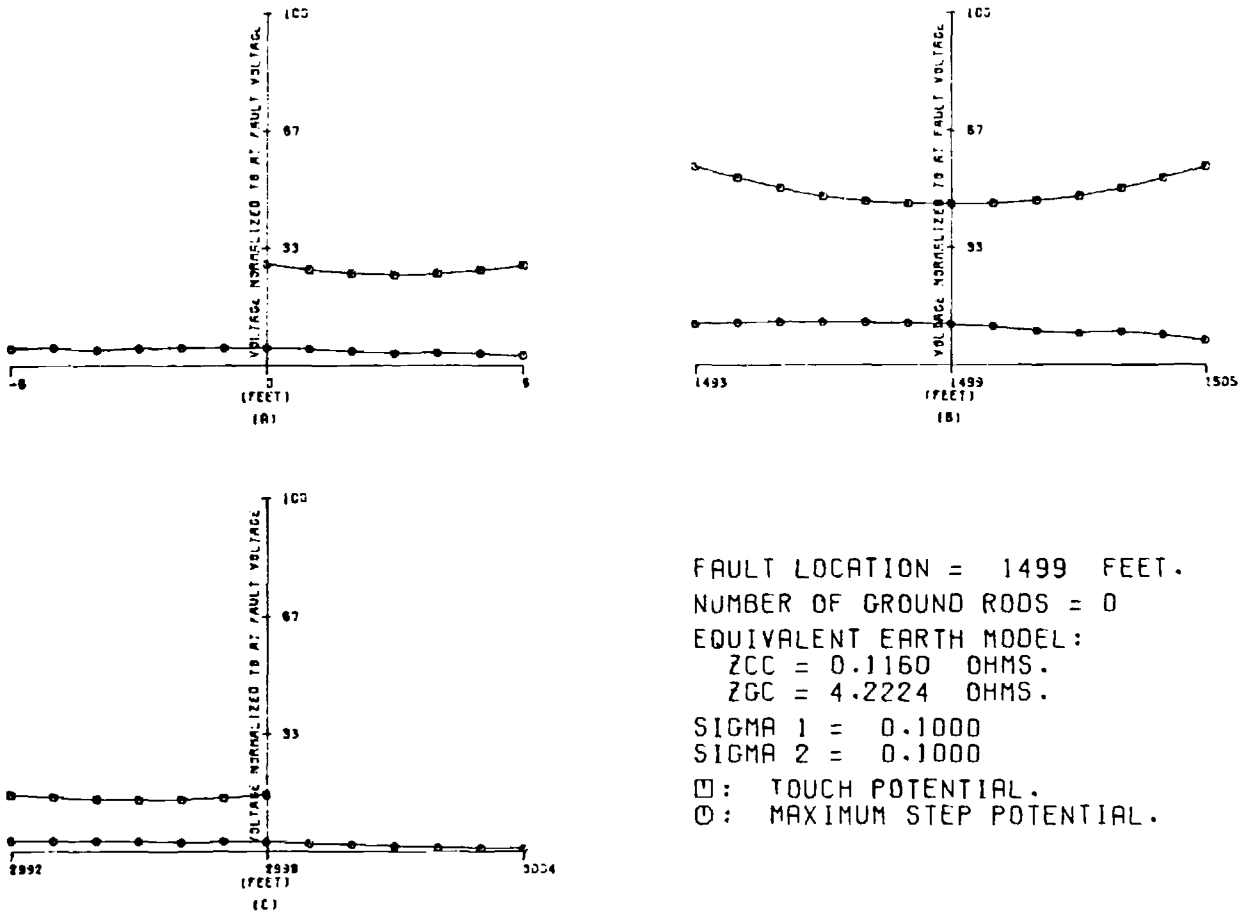
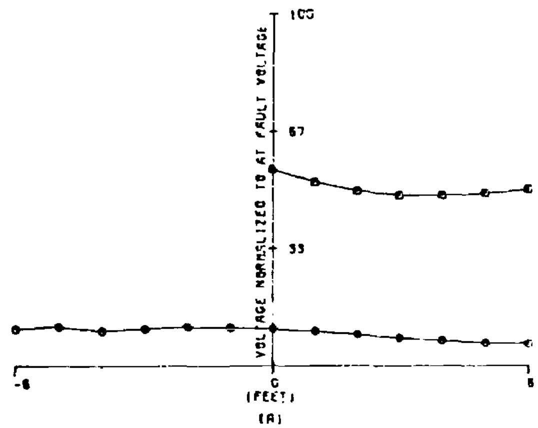


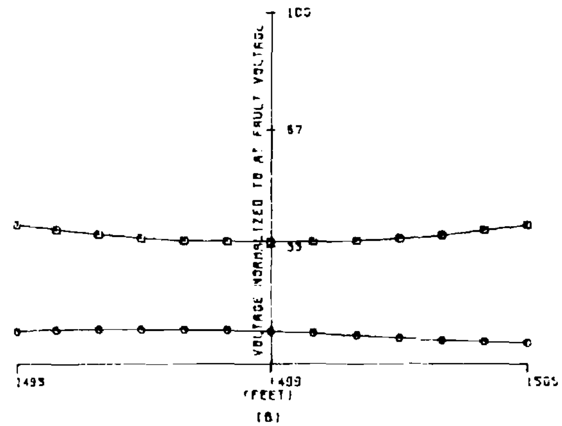
FIGURE B.30. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

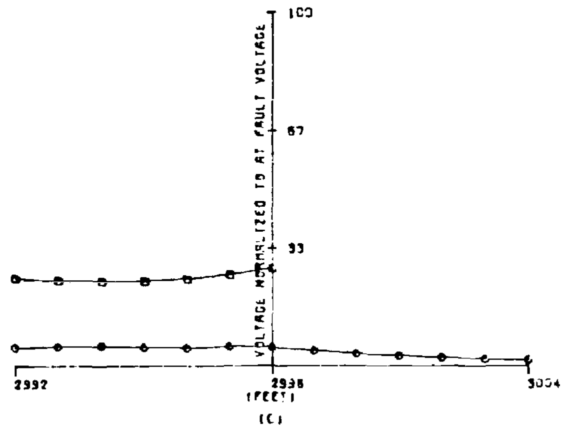


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1160 OHMS.
ZGC = 4.2224 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.31. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

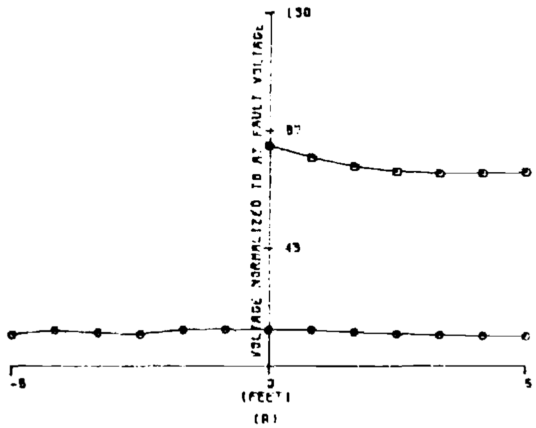


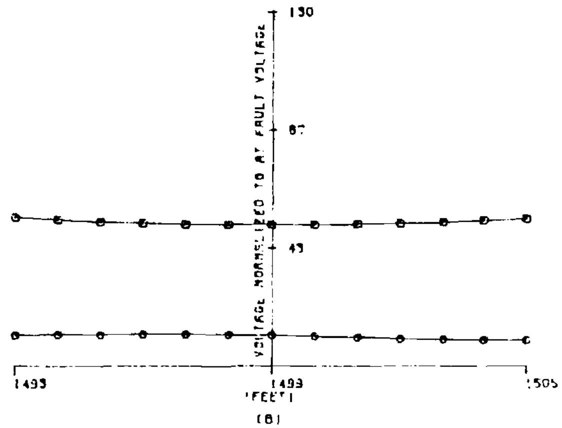


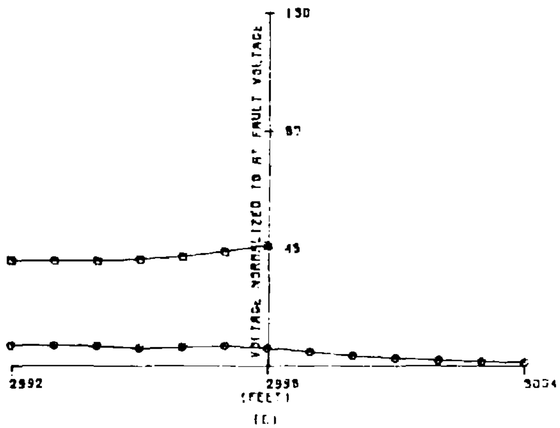


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.3082 OHMS.
ZGC = 12.6192 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.32. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

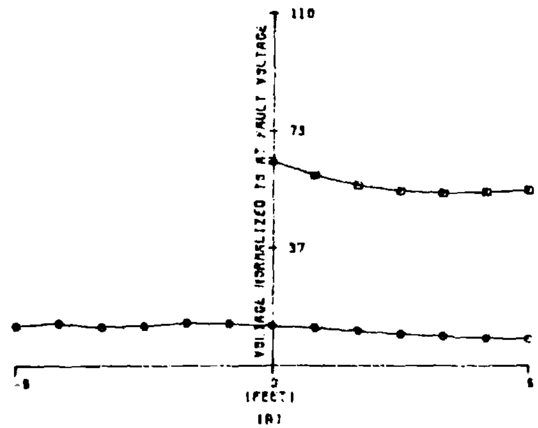


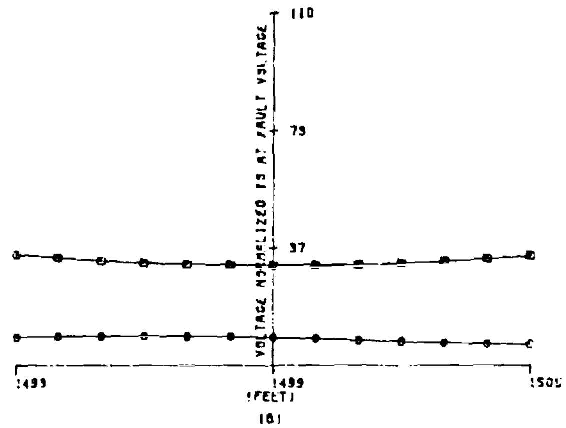


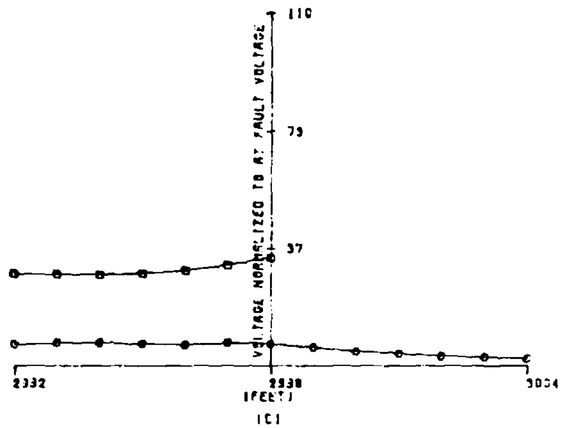


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.4799 OHMS.
ZGC = 35.7303 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.33. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

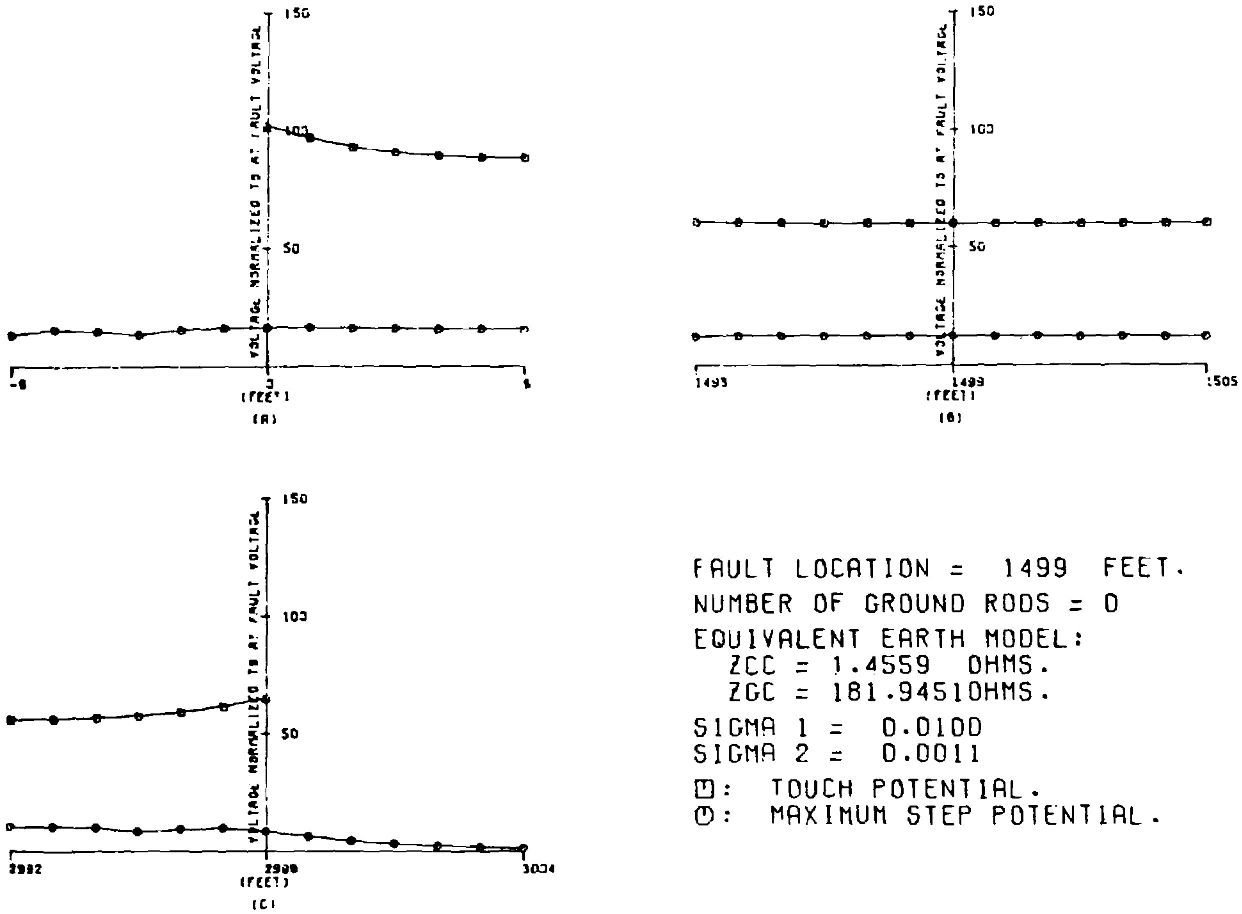






FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5621 OHMS.
ZGC = 23.3612 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.34. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 1.4559 OHMS.
ZGC = 181.94510HMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.35. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

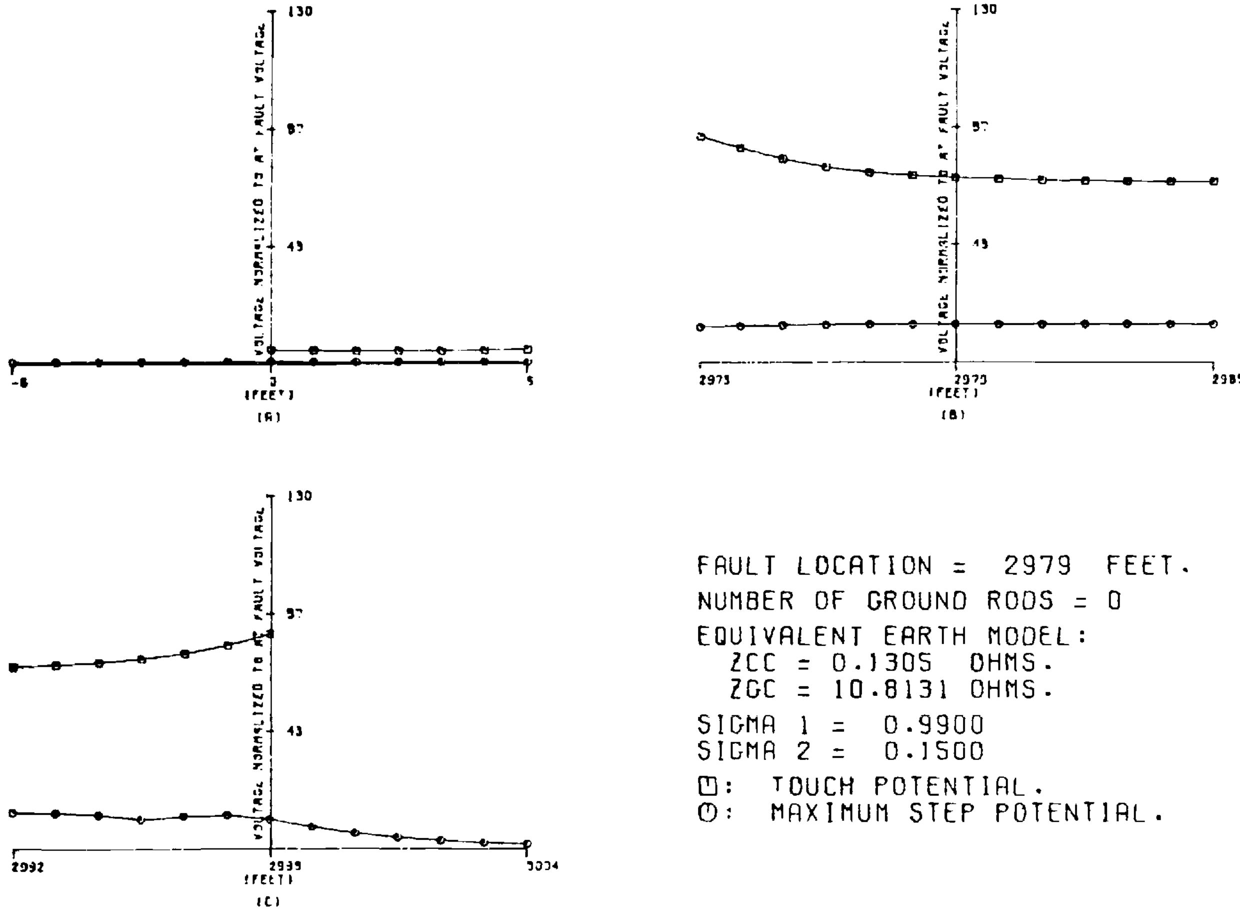
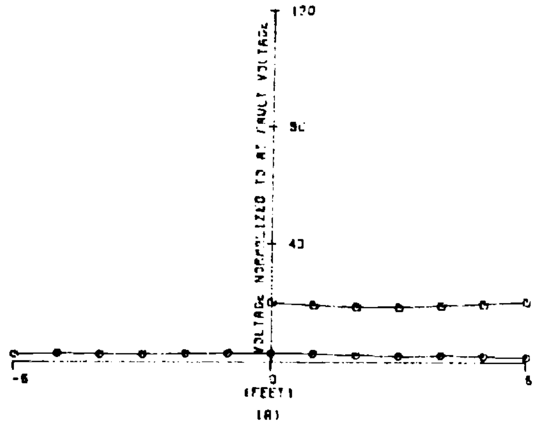
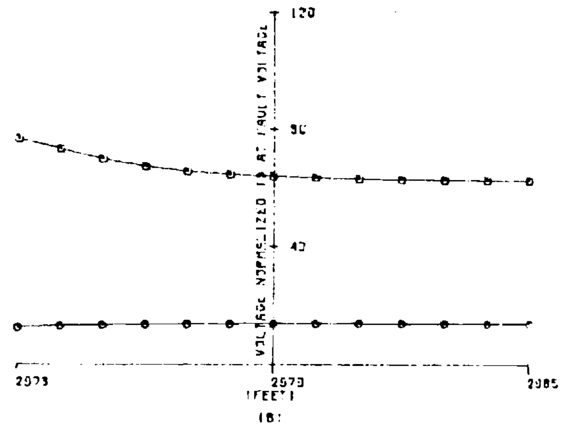
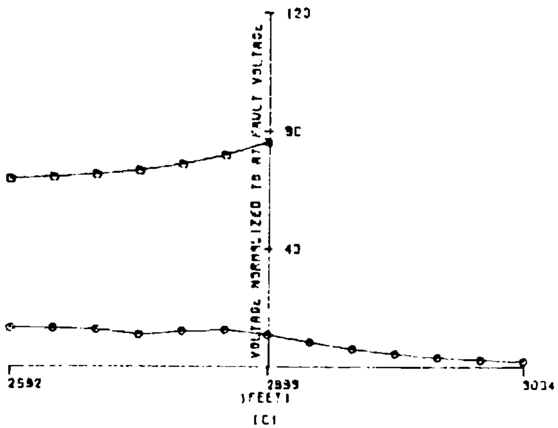


FIGURE B.36. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.2785 OHMS.
ZGC = 22.6030 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.37. TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

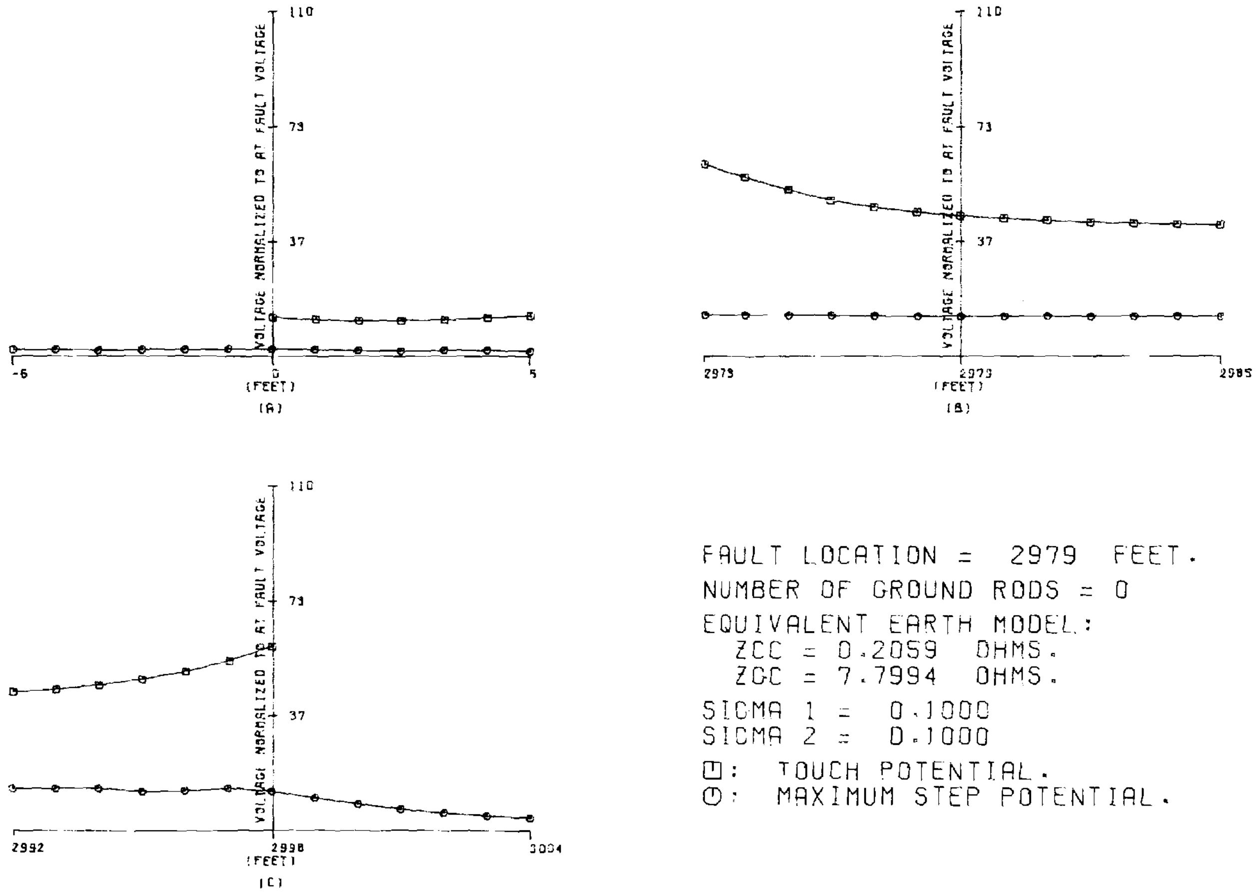
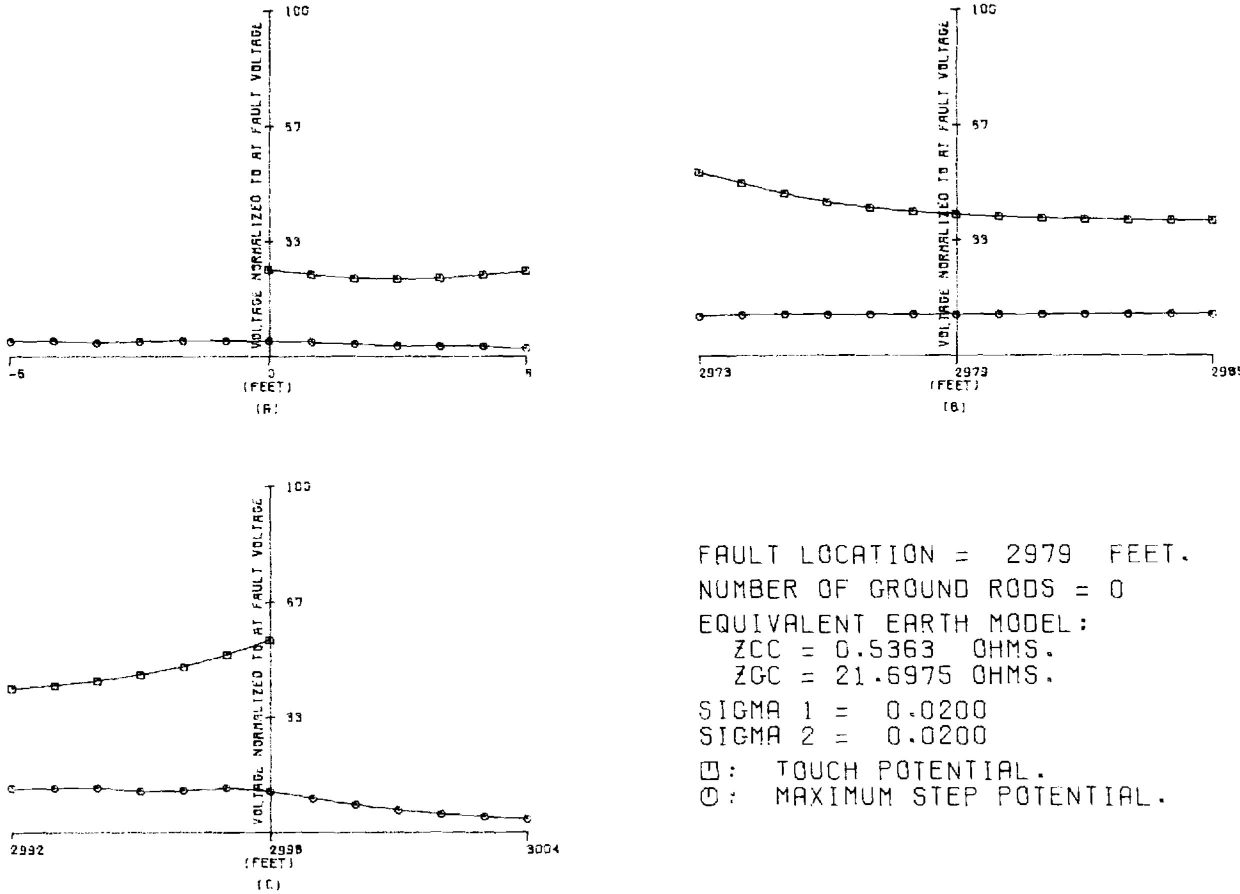
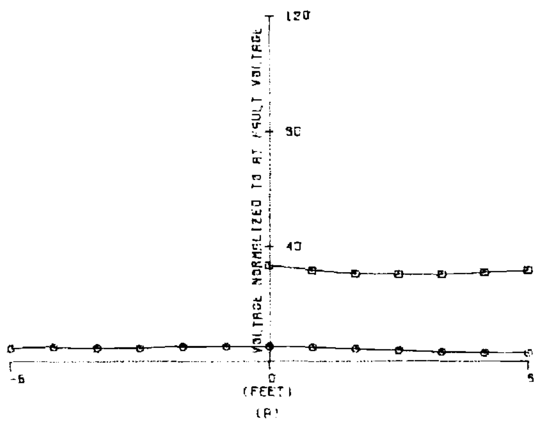


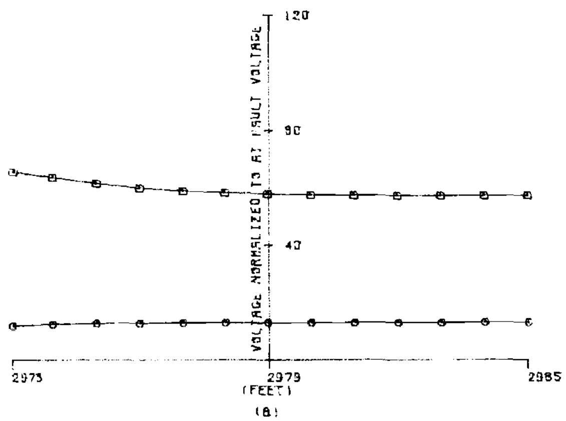
FIGURE B.38 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

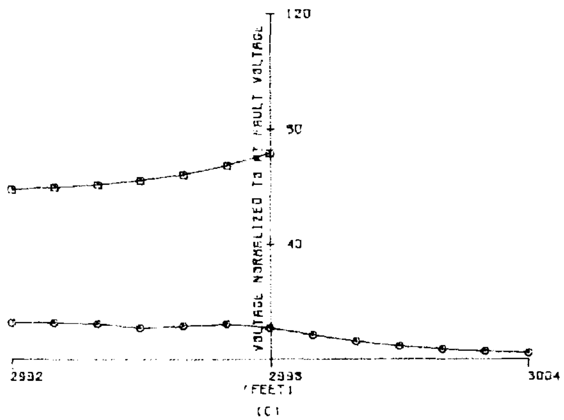


FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5363 OHMS.
ZGC = 21.6975 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.39 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 2979 FEET.

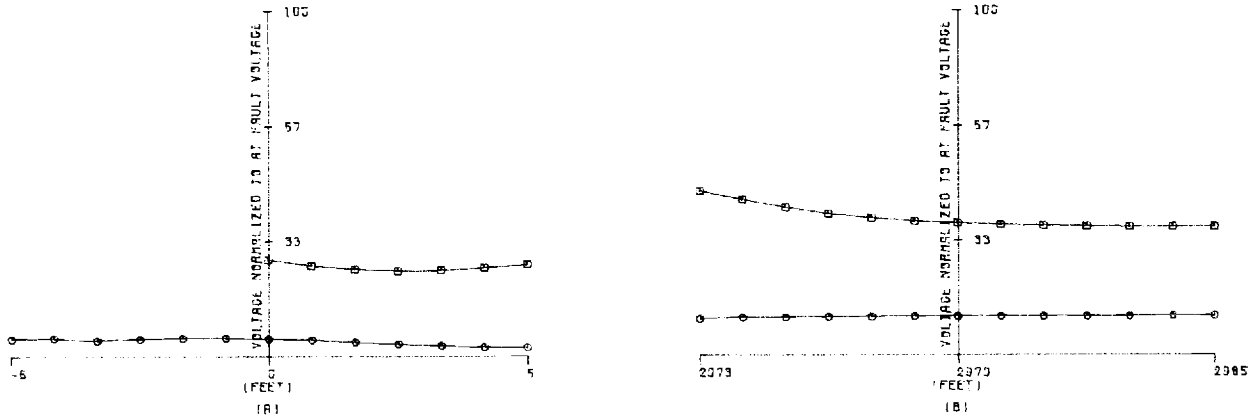
NUMBER OF GROUND RODS = 0

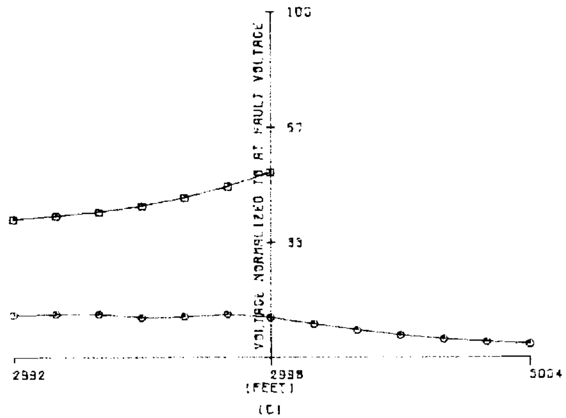
EQUIVALENT EARTH MODEL:
ZCC = 0.8333 OHMS.
ZGC = 60.8922 OHMS.

SIGMA 1 = 0.0200
SIGMA 2 = 0.0050

□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.40 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.

NUMBER OF GROUND RODS = 0

EQUIVALENT EARTH MODEL:

ZCC = 0.9741 OHMS.

ZGC = 39.5595 OHMS.

SIGMA 1 = 0.0100

SIGMA 2 = 0.0100

□: TOUCH POTENTIAL.

○: MAXIMUM STEP POTENTIAL.

FIGURE B.41 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

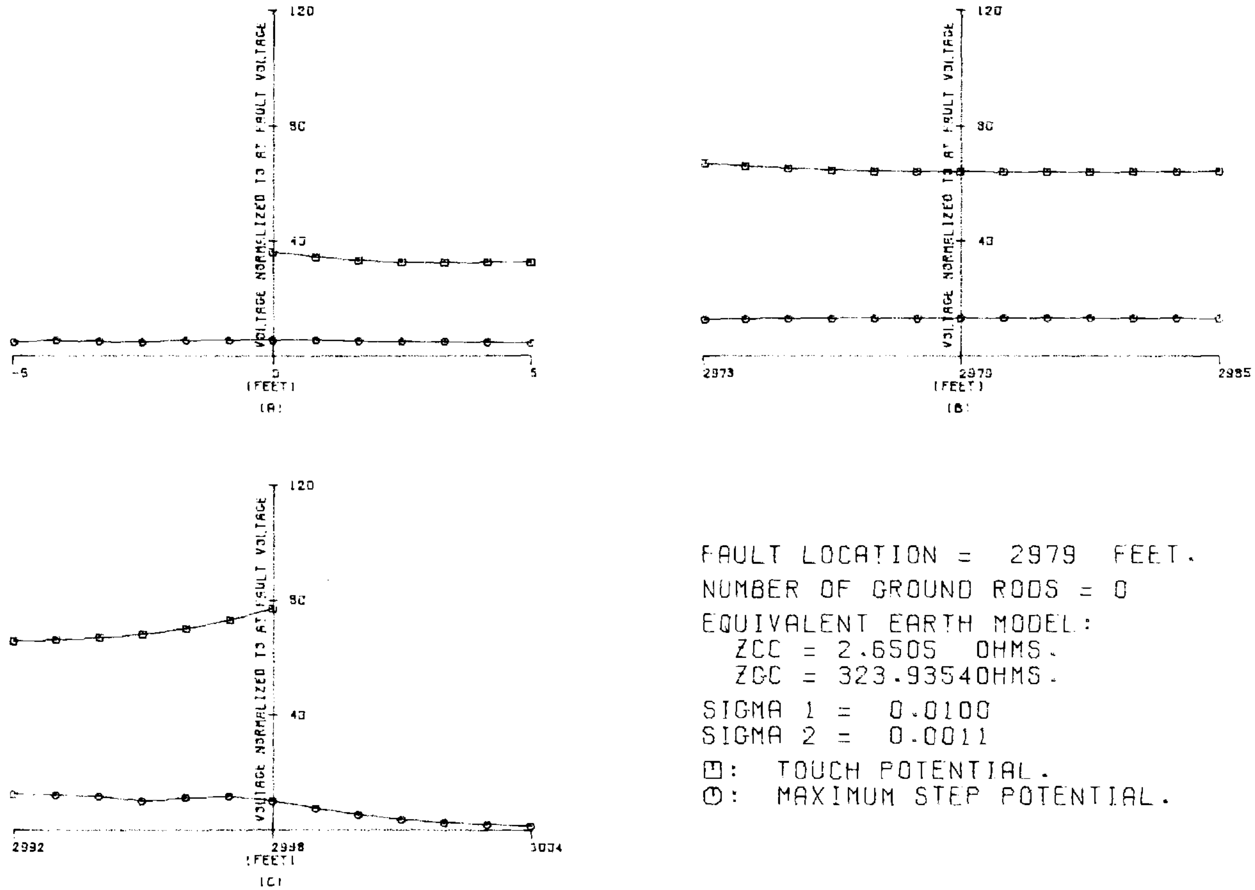


FIGURE B.42 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

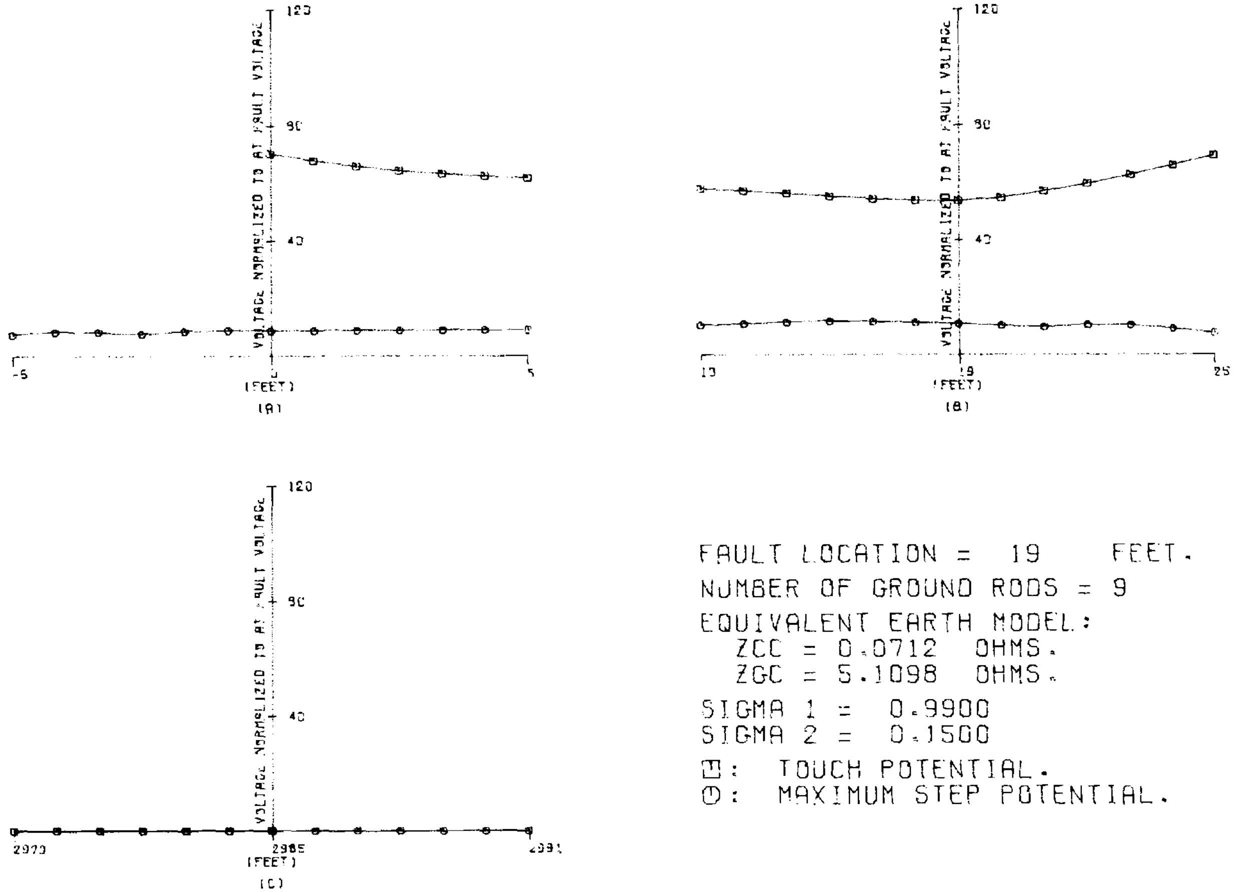
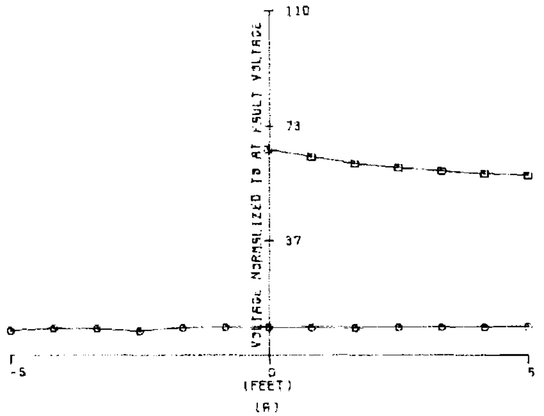
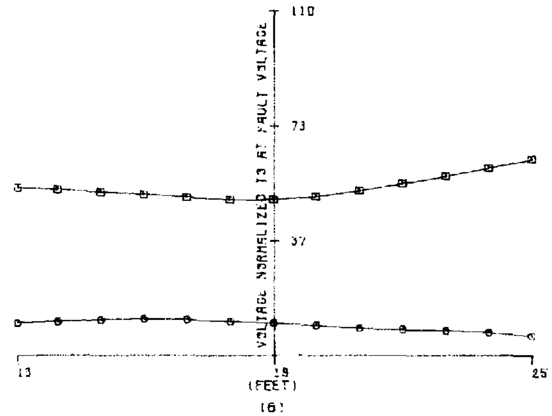
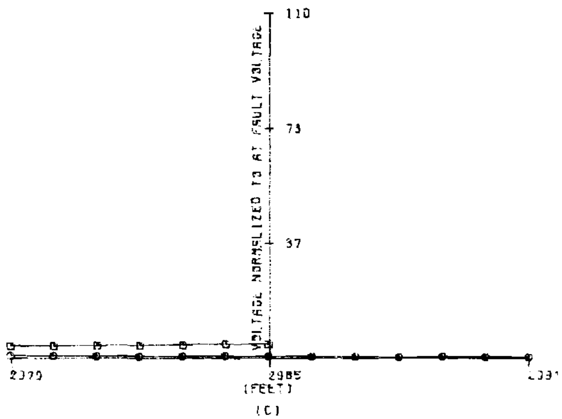


FIGURE B.43 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1528 OHMS.
ZGC = 11.4823 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.44 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

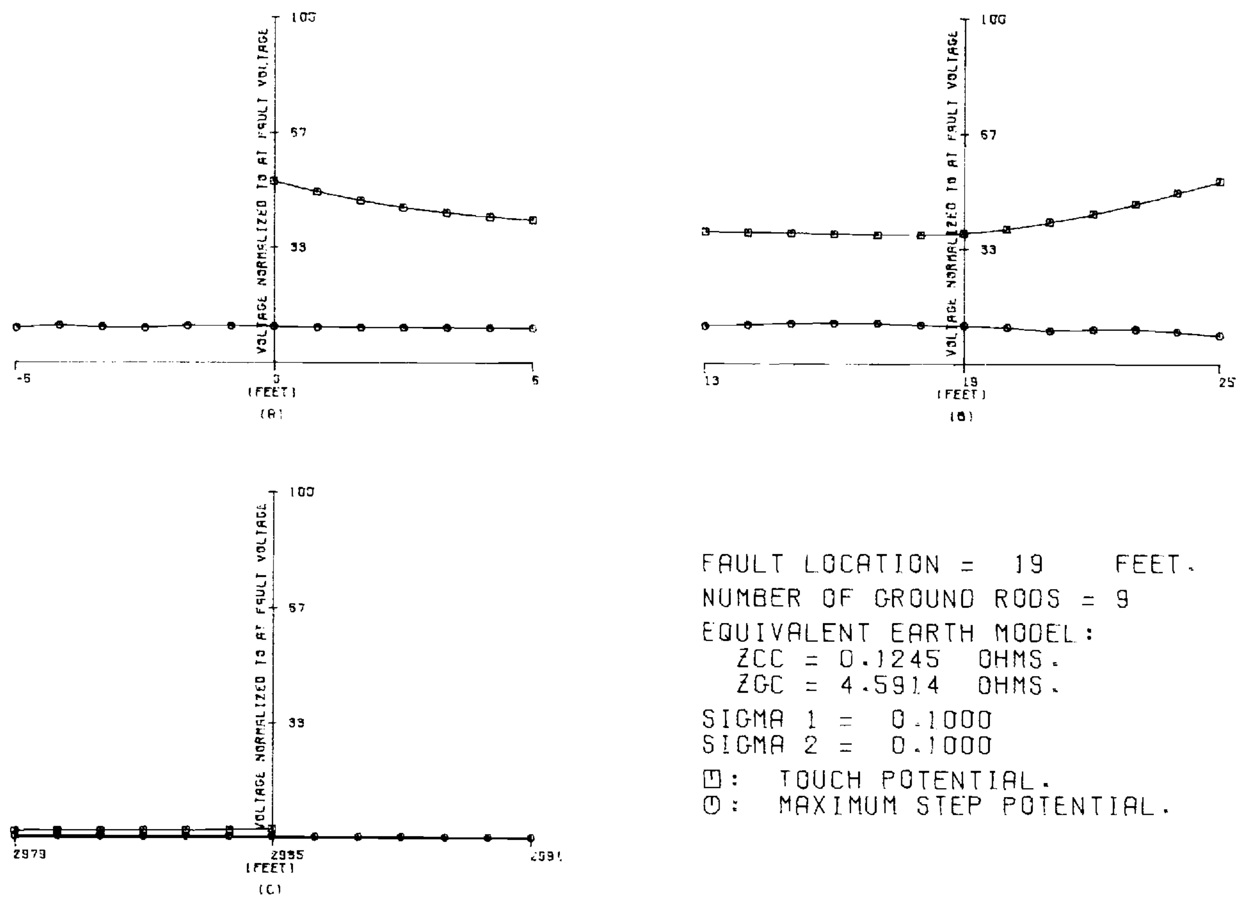


FIGURE B.45 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

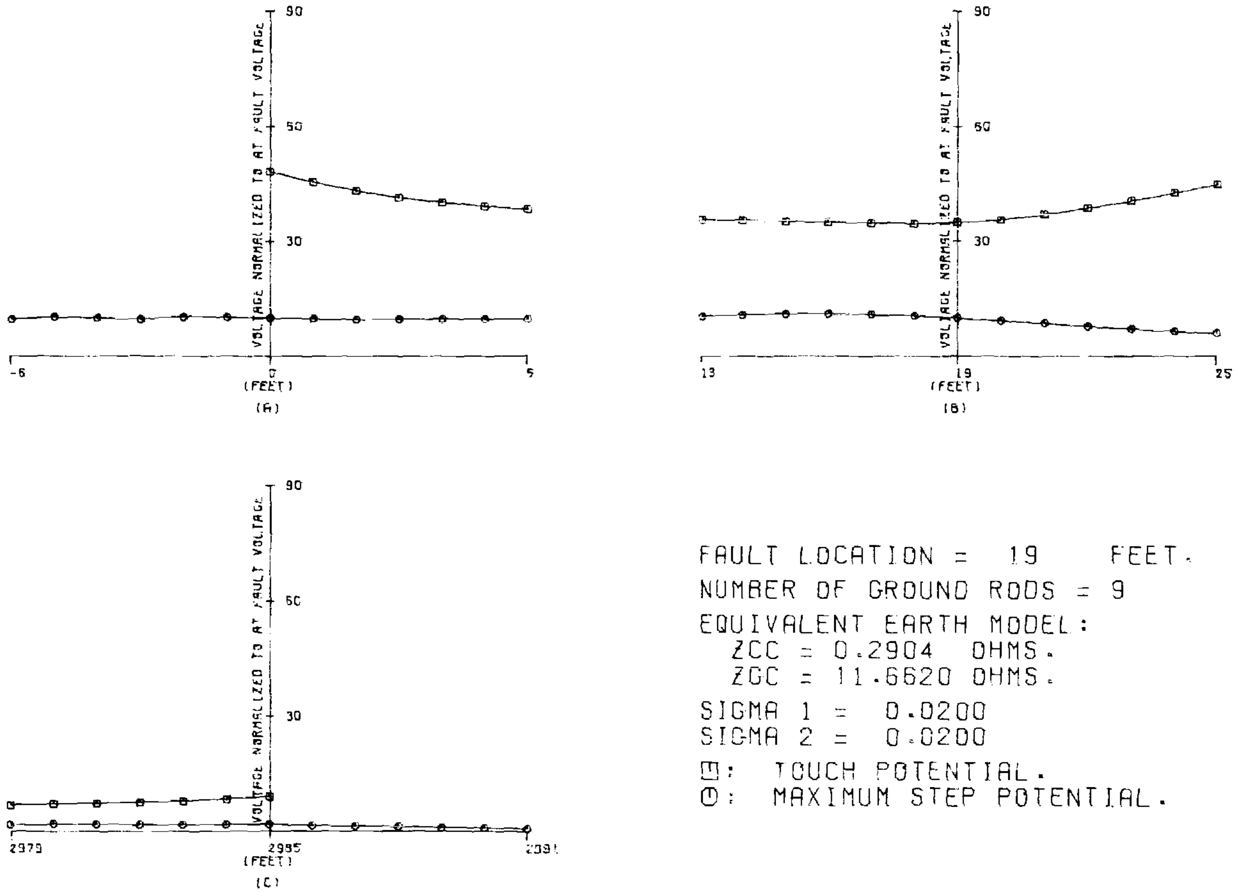
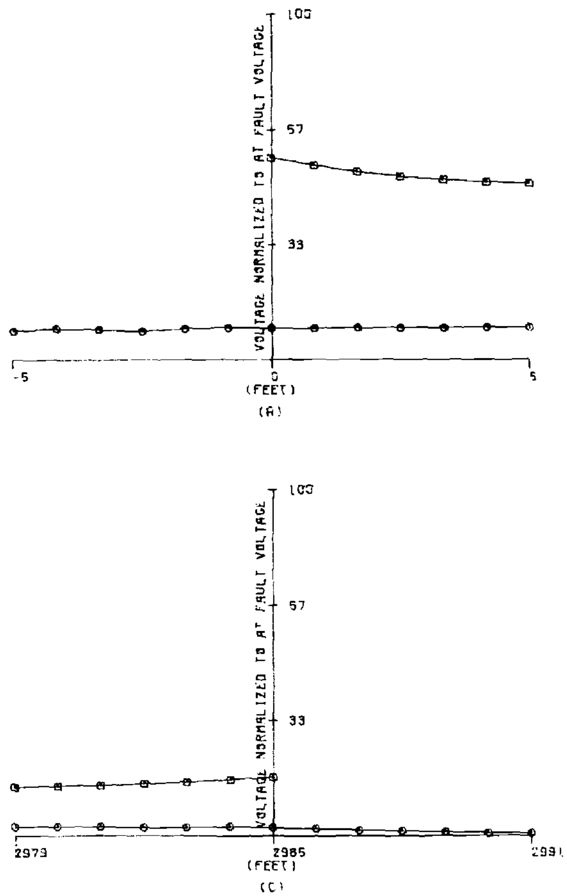


FIGURE B.46 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.3855 OHMS.
ZGC = 30.2939 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.47 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

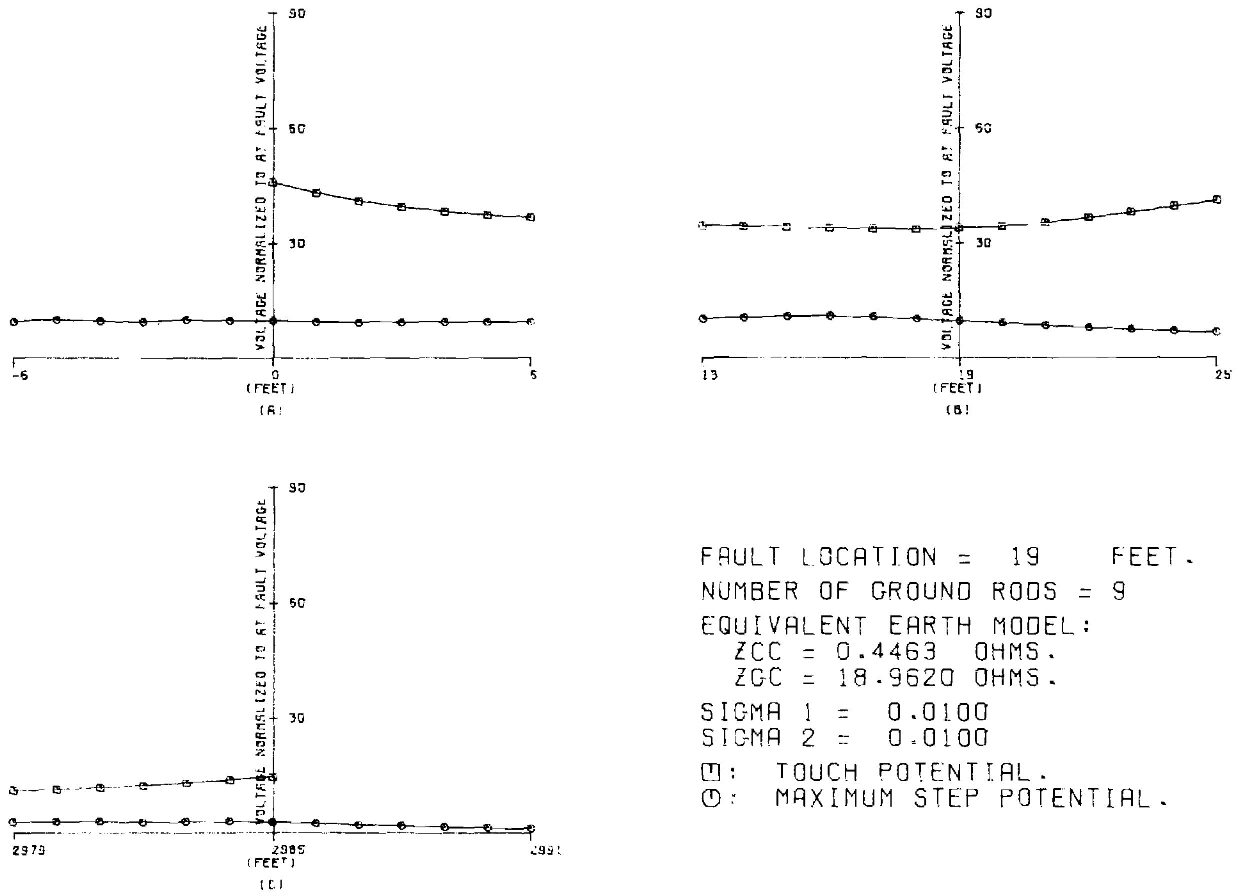
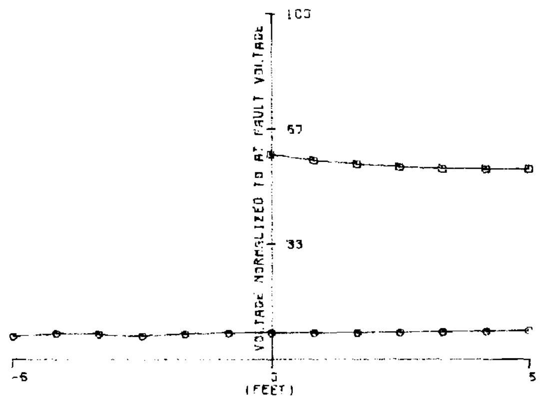
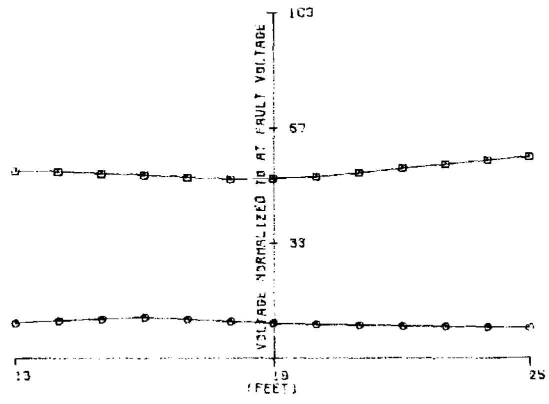
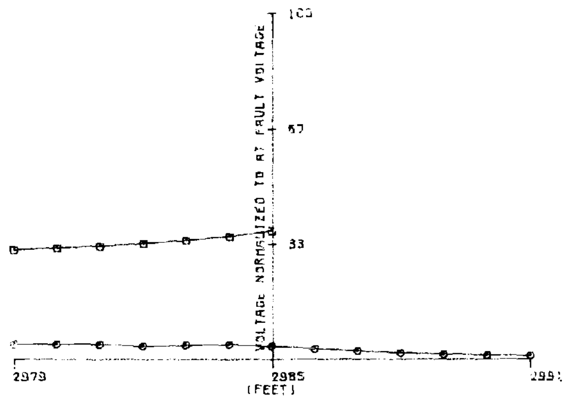


FIGURE B.48 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

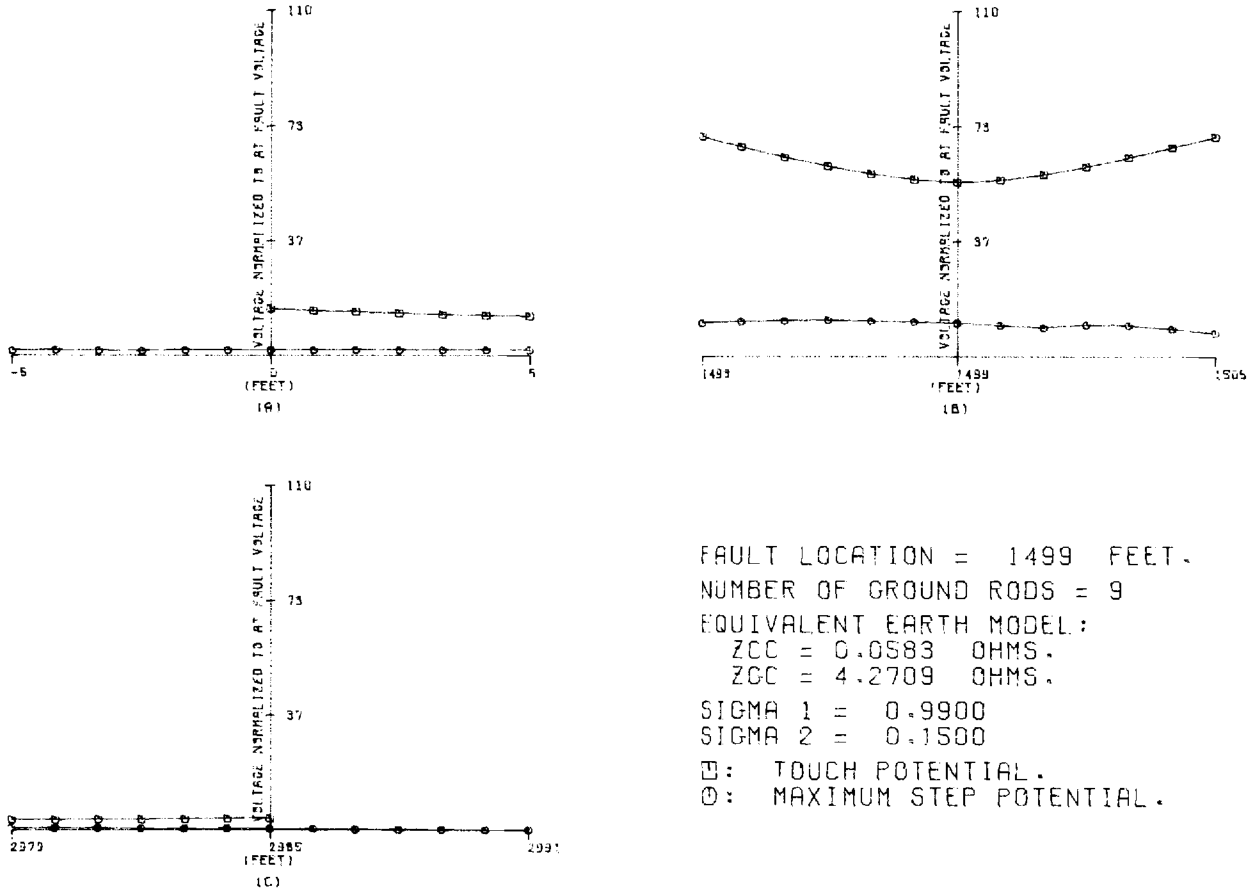






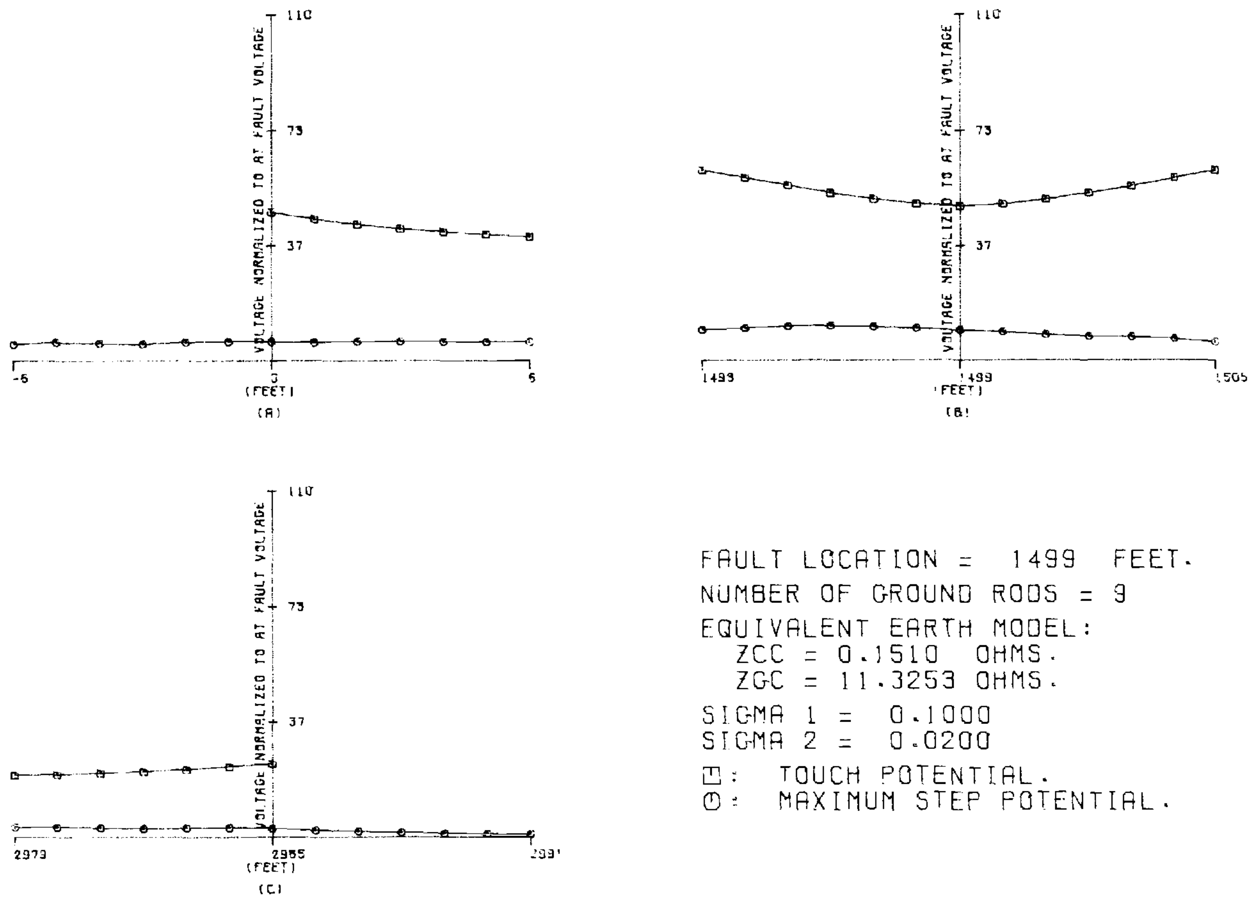
FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.7773 OHMS.
ZGC = 104.2811OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.49 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.0583 OHMS.
ZGC = 4.2709 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.50 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1510 OHMS.
ZGC = 11.3253 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.51 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

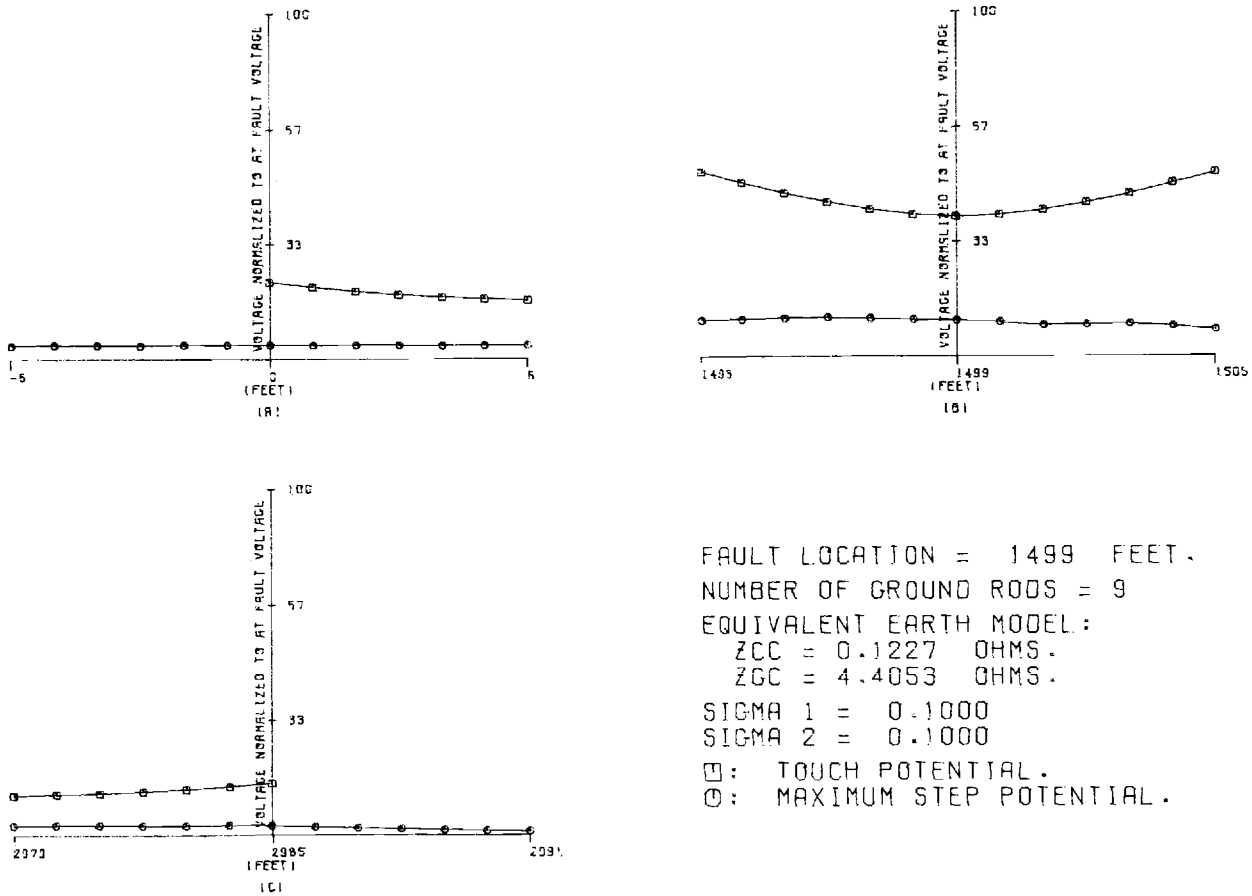


FIGURE B.52 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

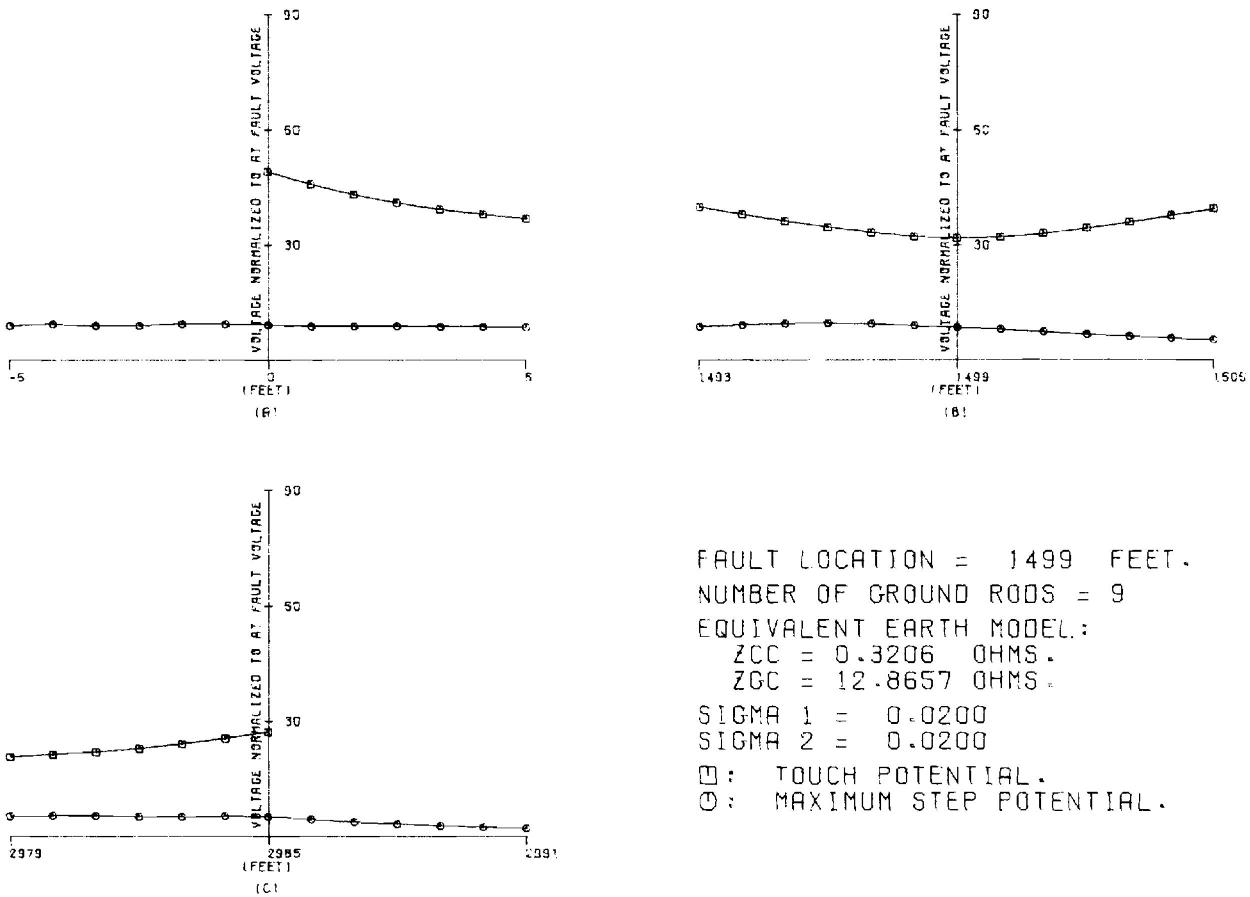


FIGURE B.53 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

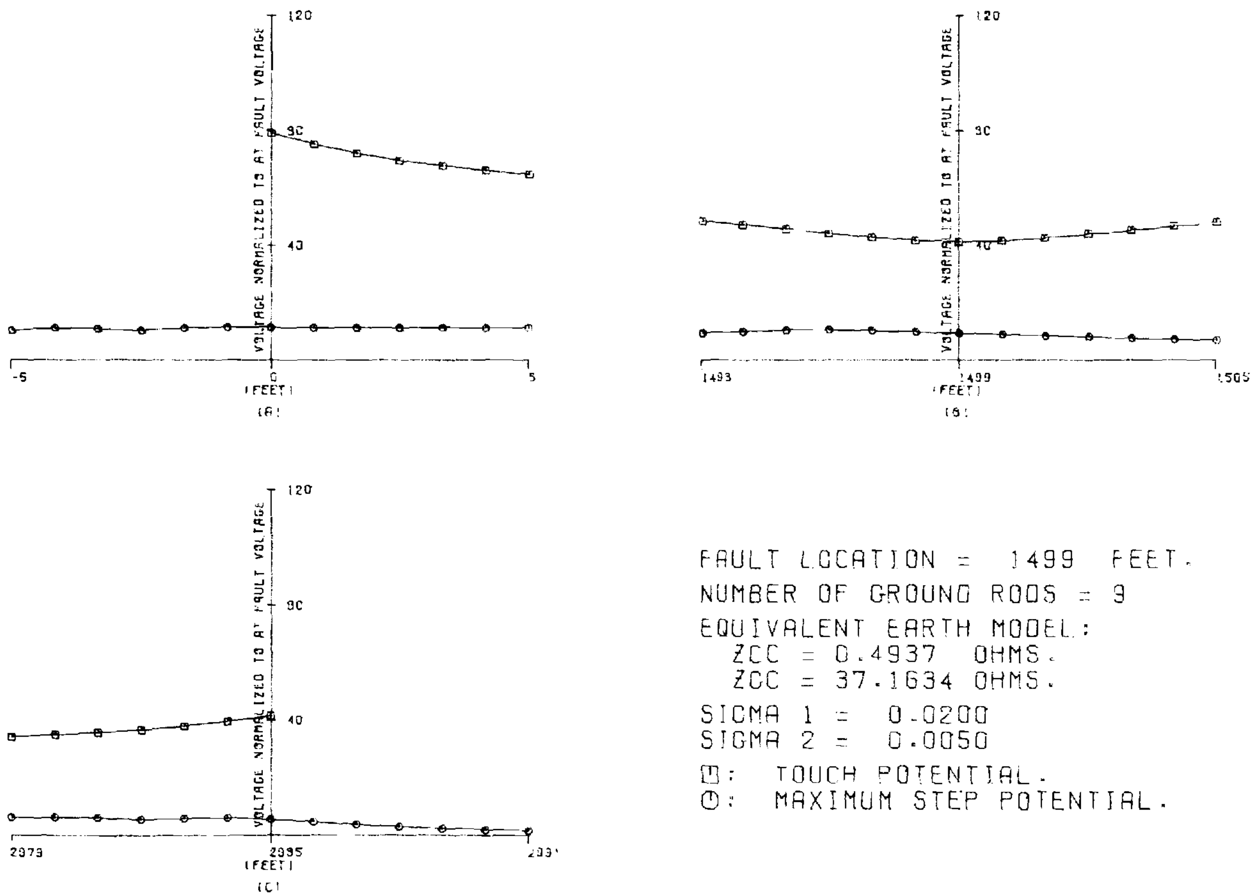
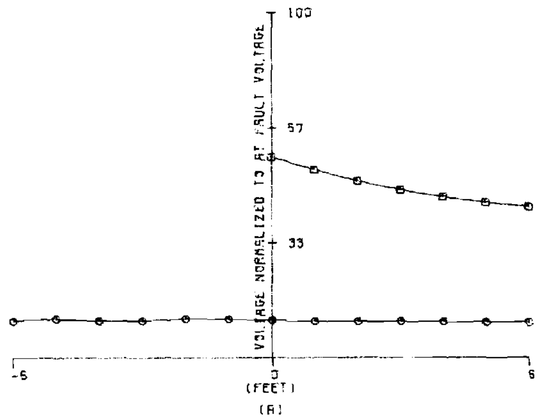
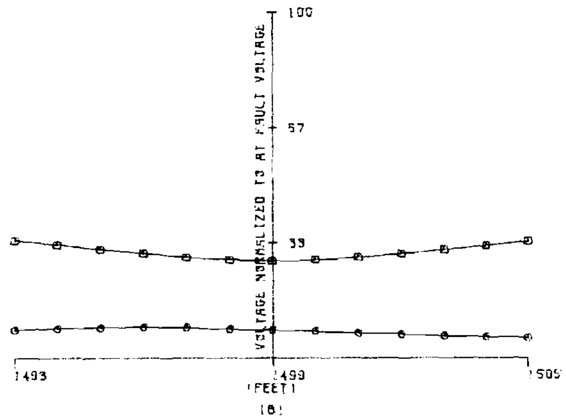
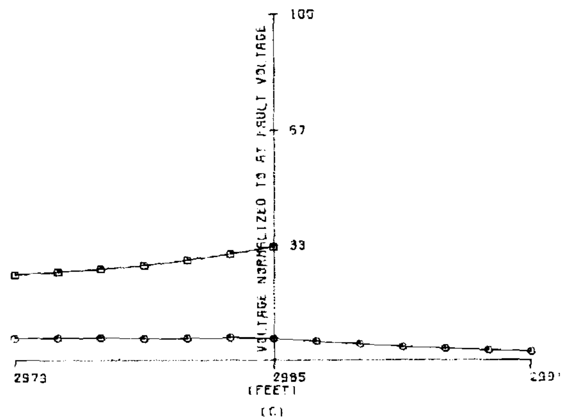


FIGURE B.54 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.5750 OHMS.
ZGC = 23.4730 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.55 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

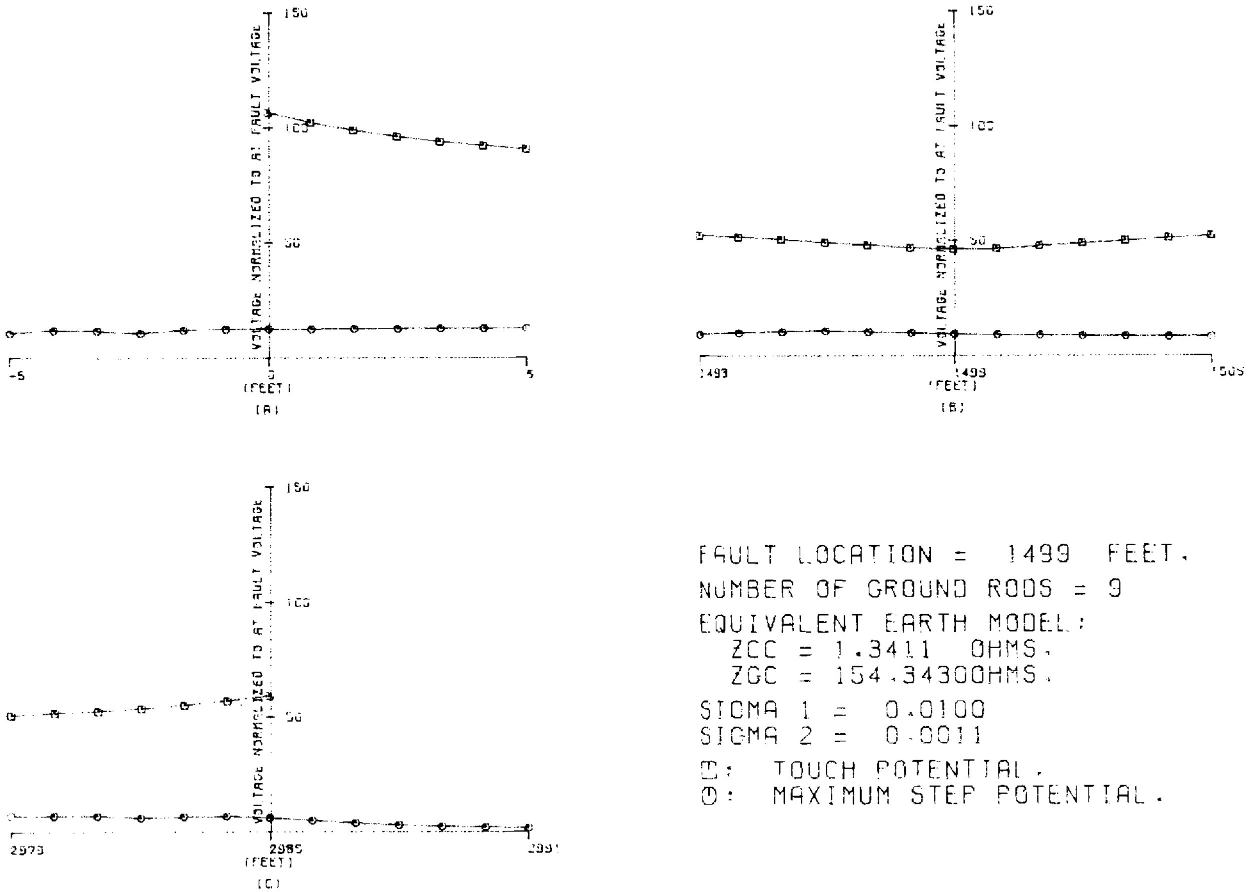


FIGURE B.56 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

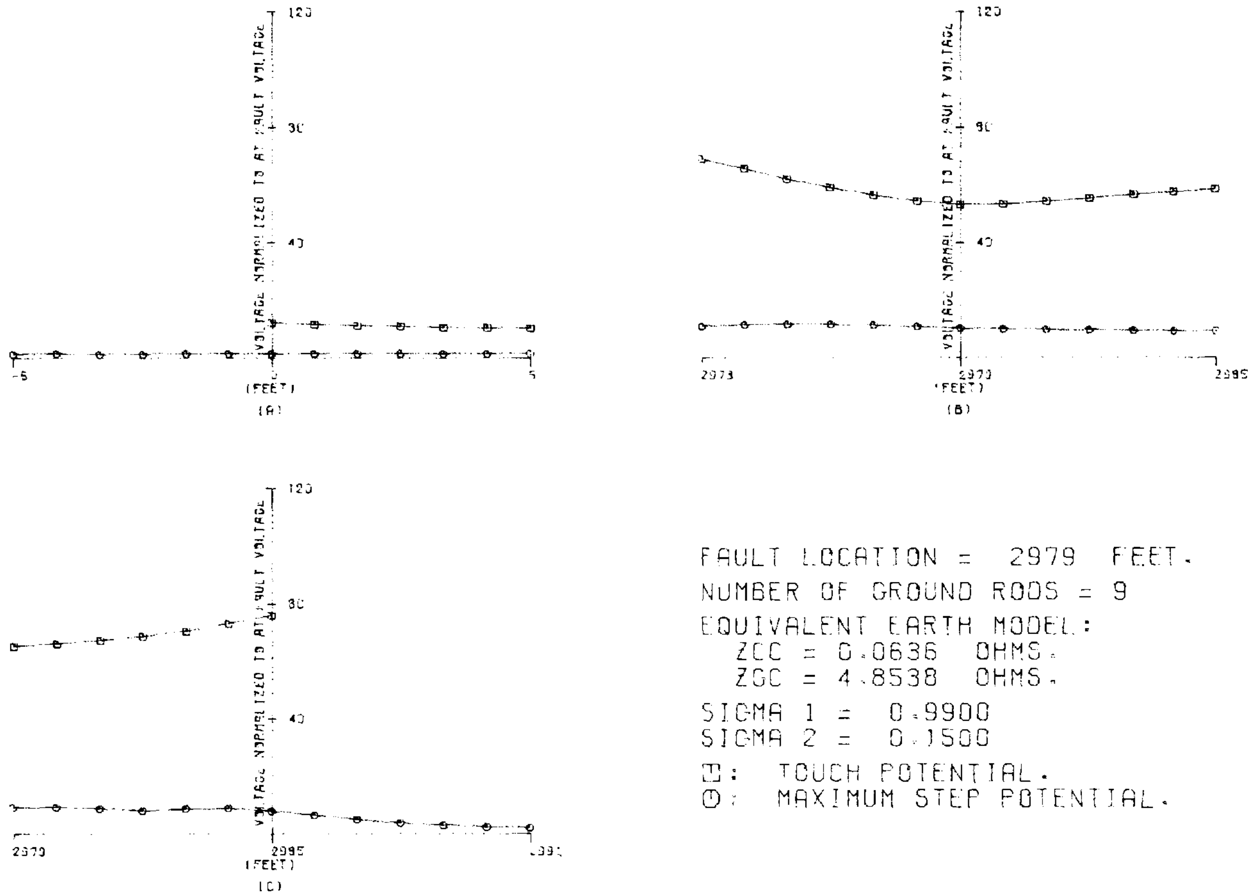


FIGURE B.57 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

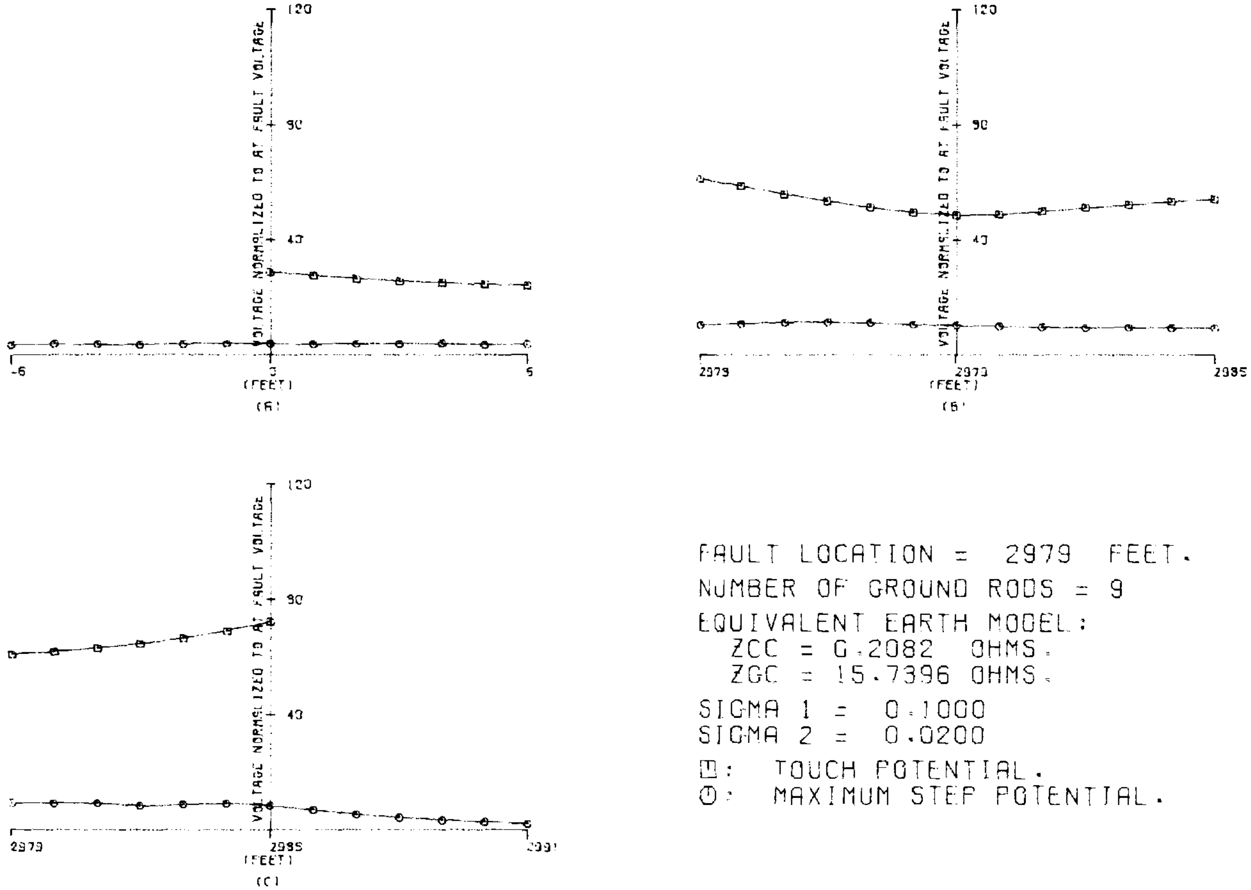


FIGURE B.58 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

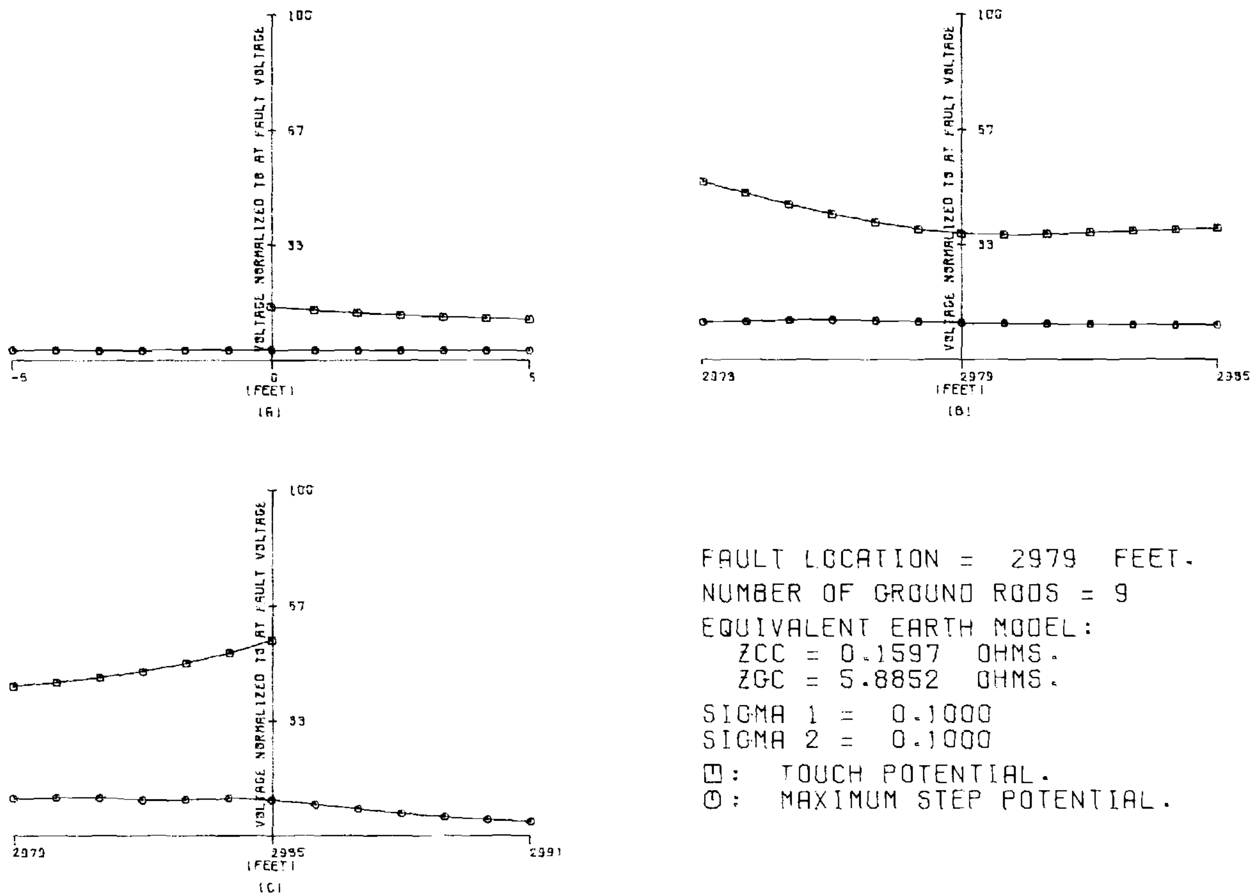


FIGURE B.59 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

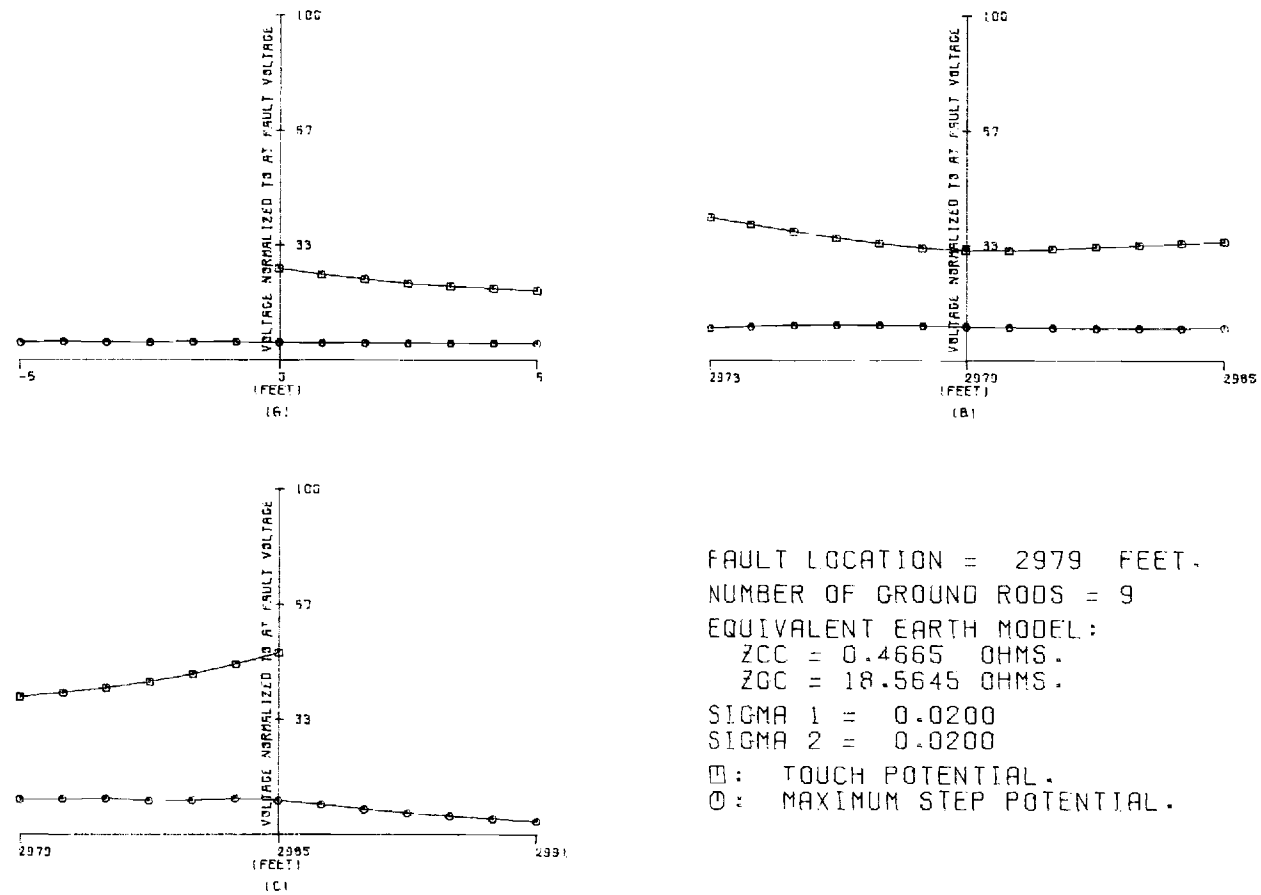


FIGURE B.60 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

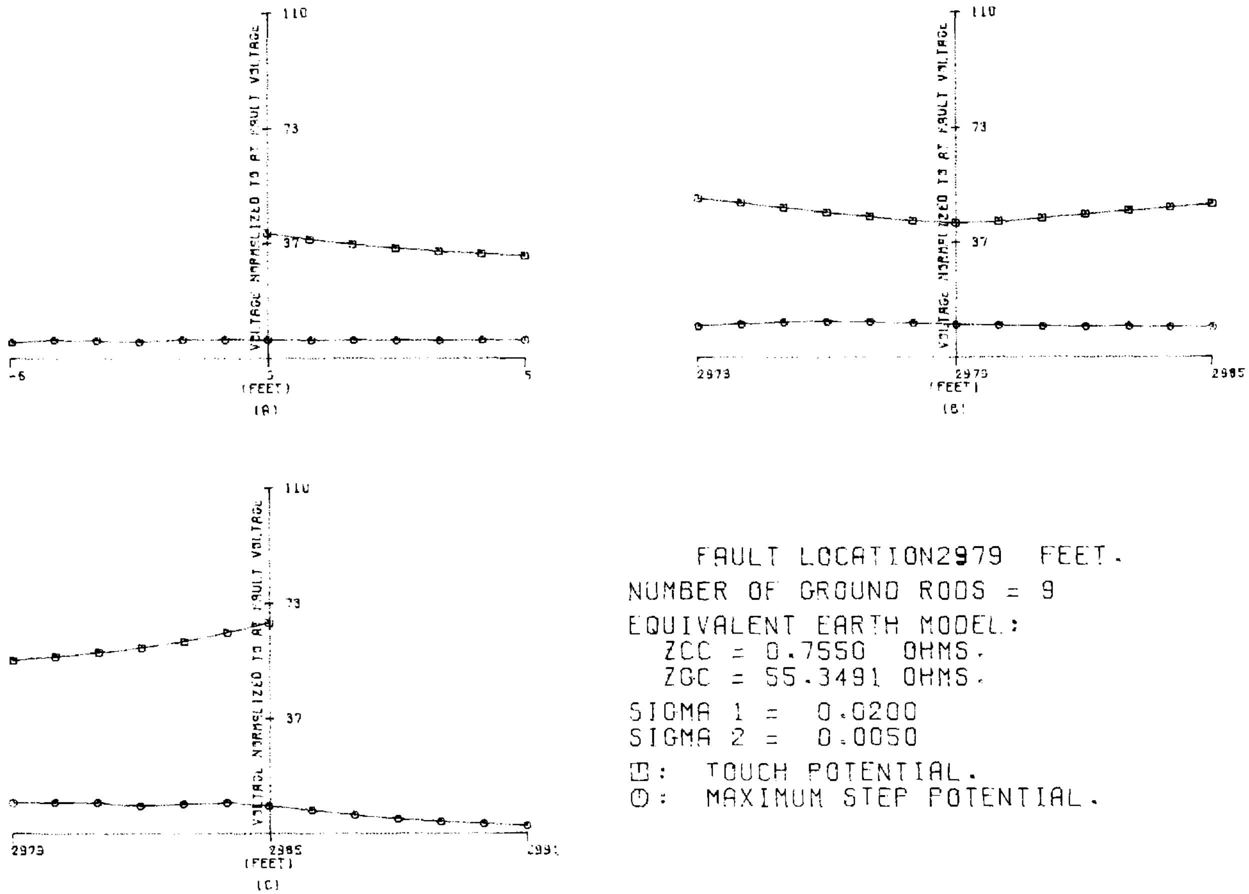


FIGURE B.61 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

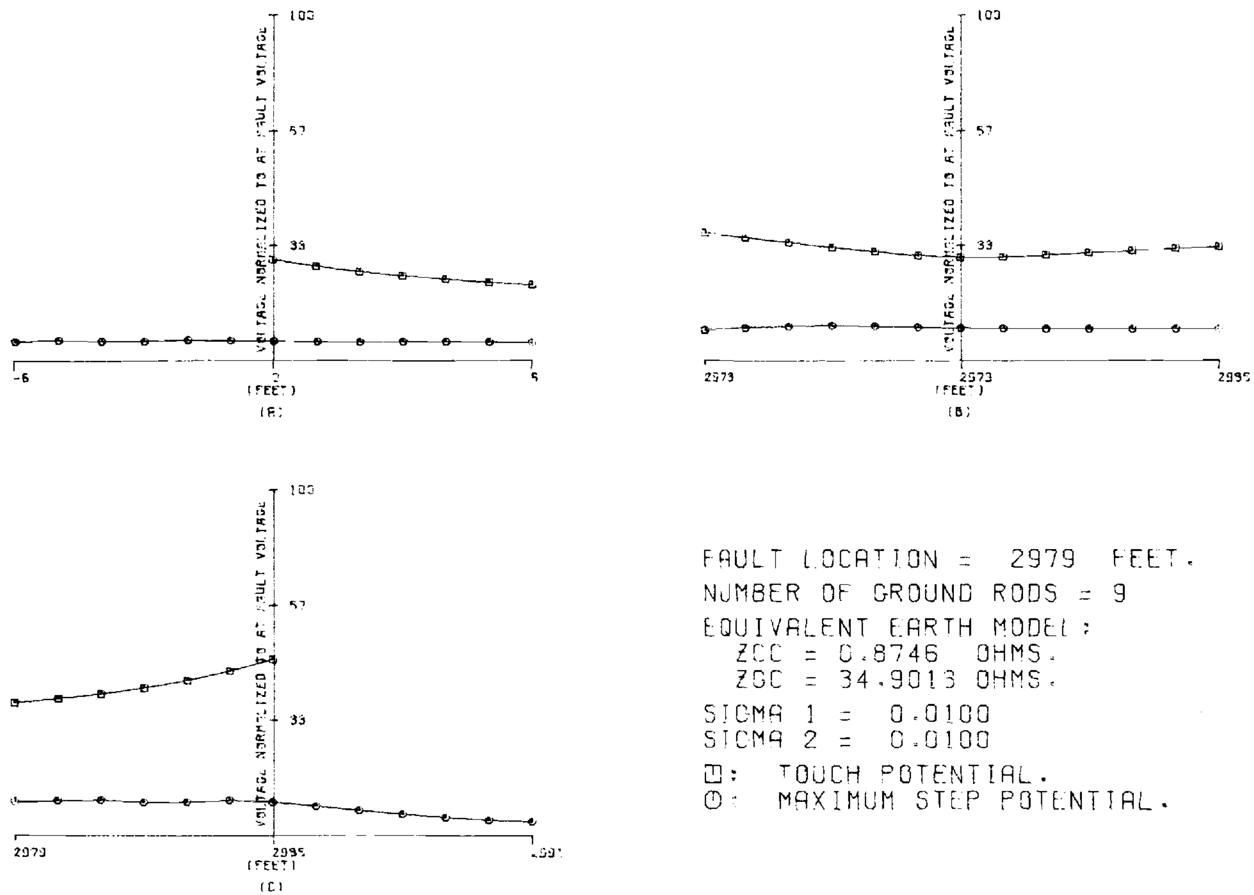
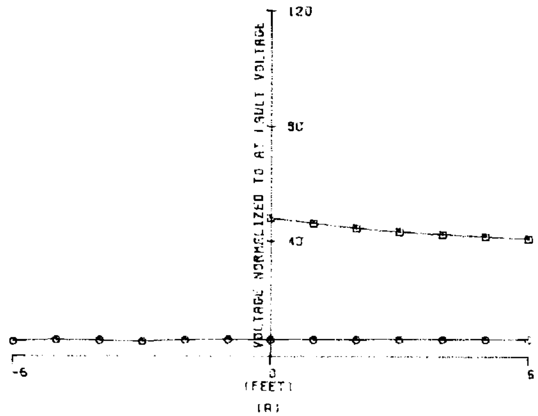
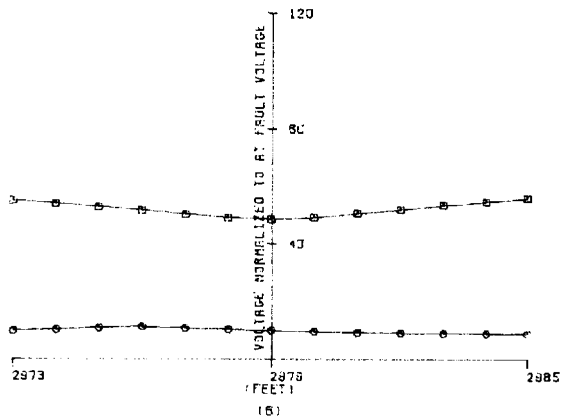
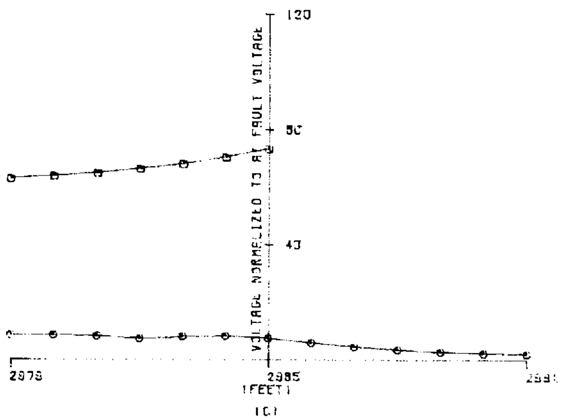


FIGURE B.62 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 2.2012 OHMS.
ZGC = 242.2408OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.63 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

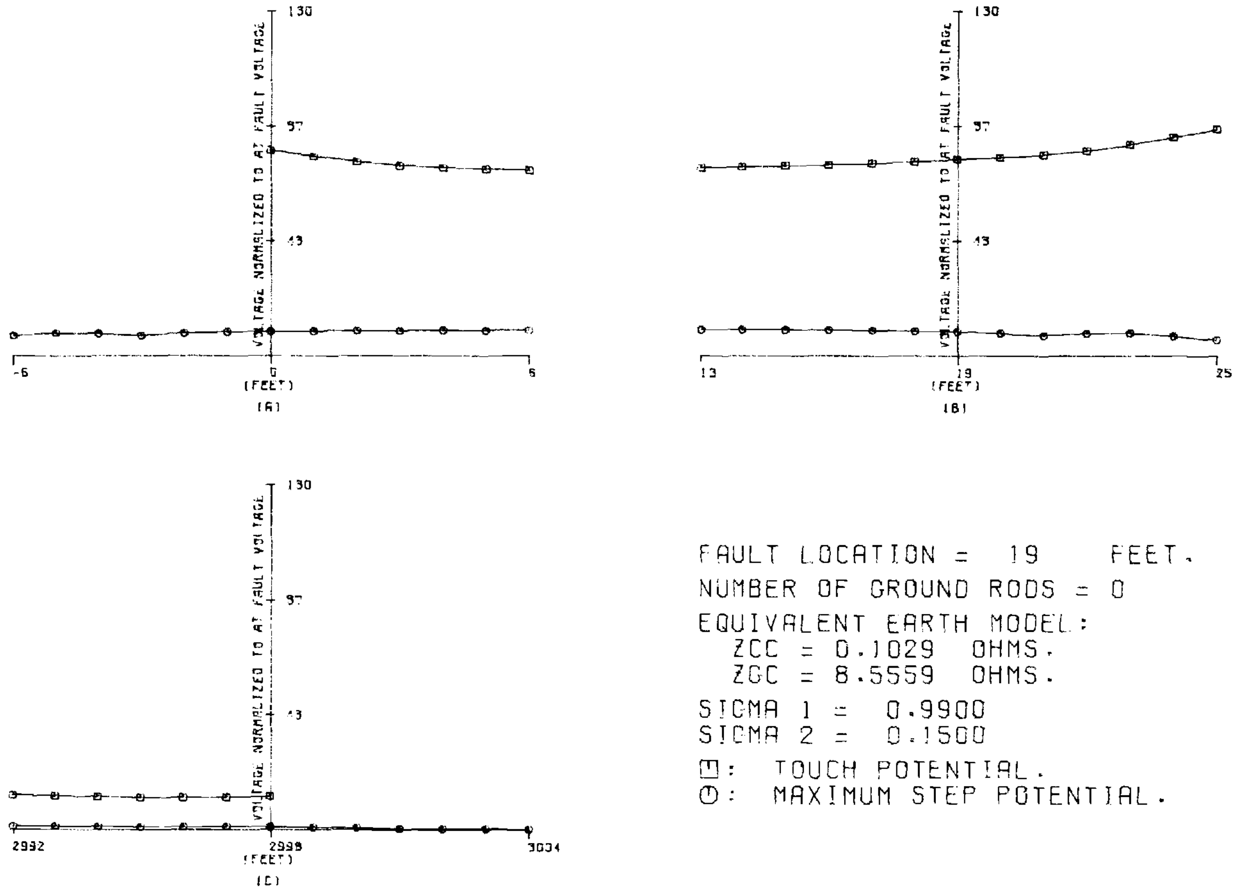


FIGURE B.64 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

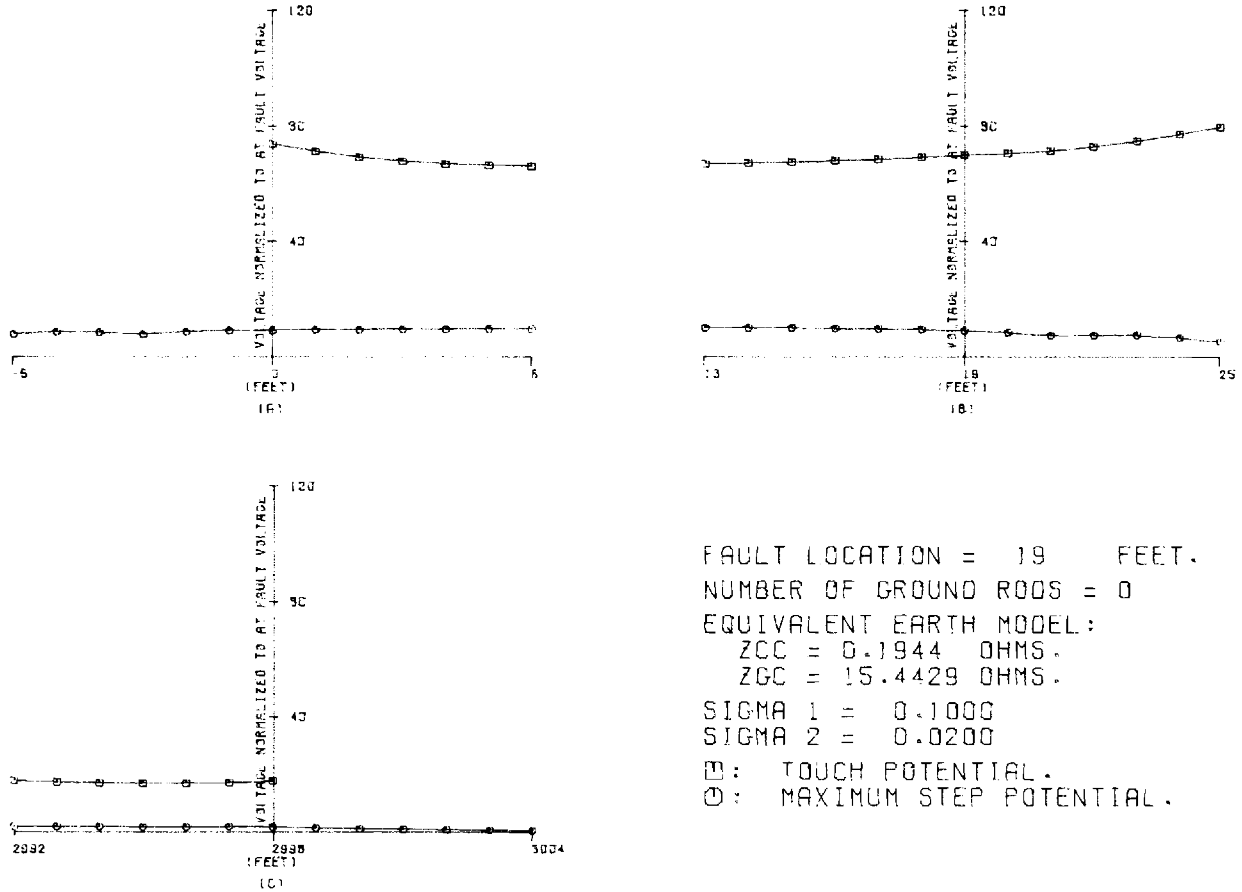
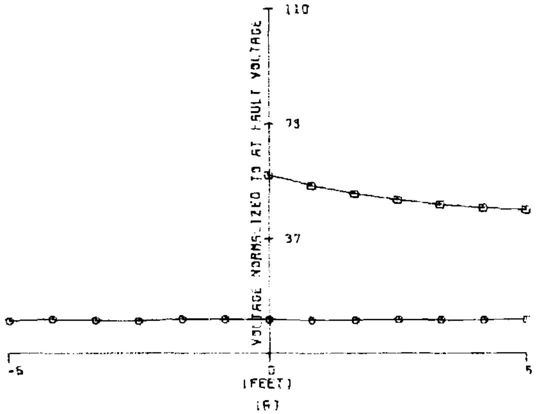
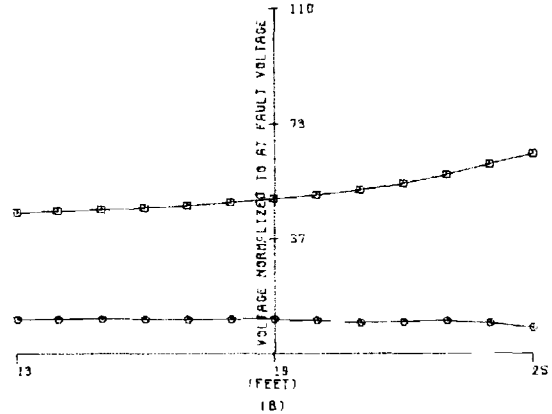
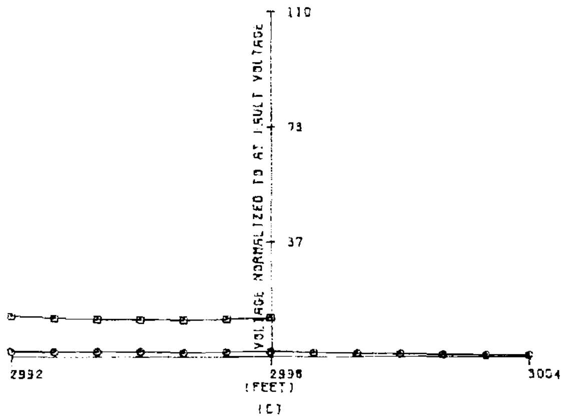


FIGURE B.65 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

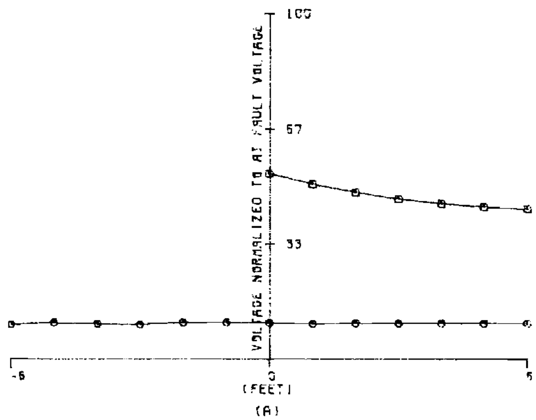


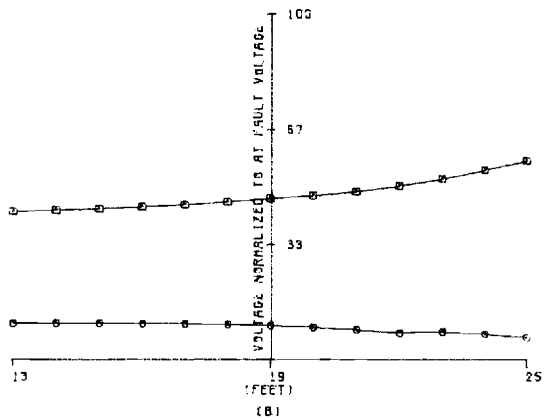


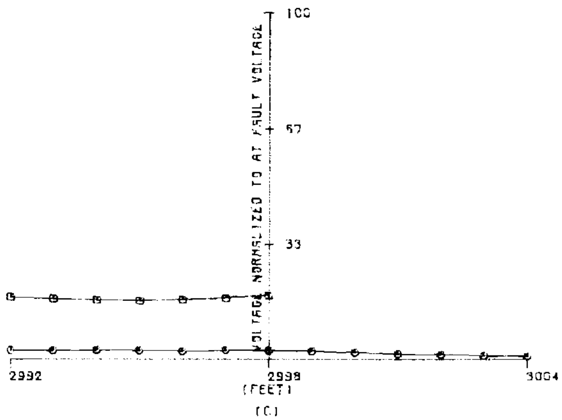


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1472 OHMS.
ZGC = 5.7526 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.66 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.3482 OHMS.
ZGC = 13.7958 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.67 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

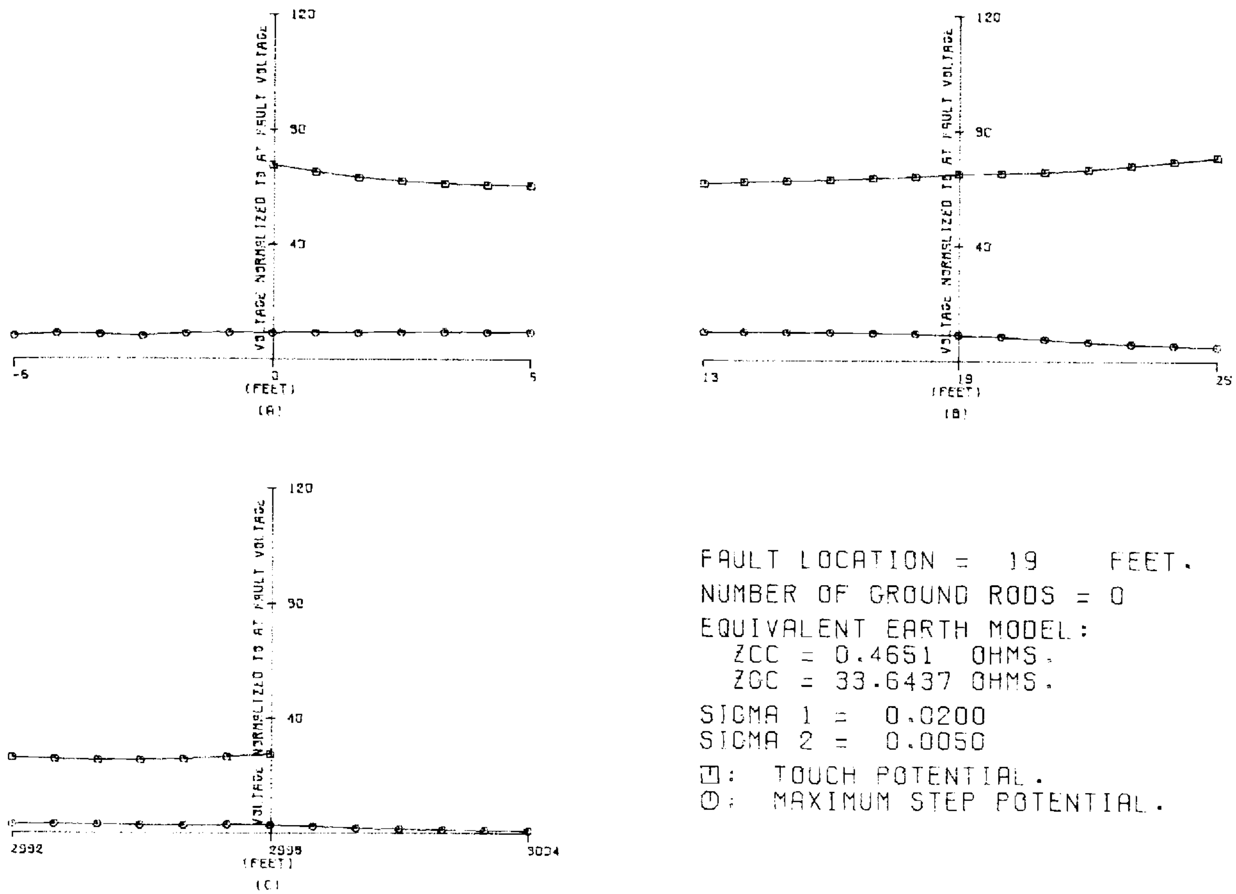
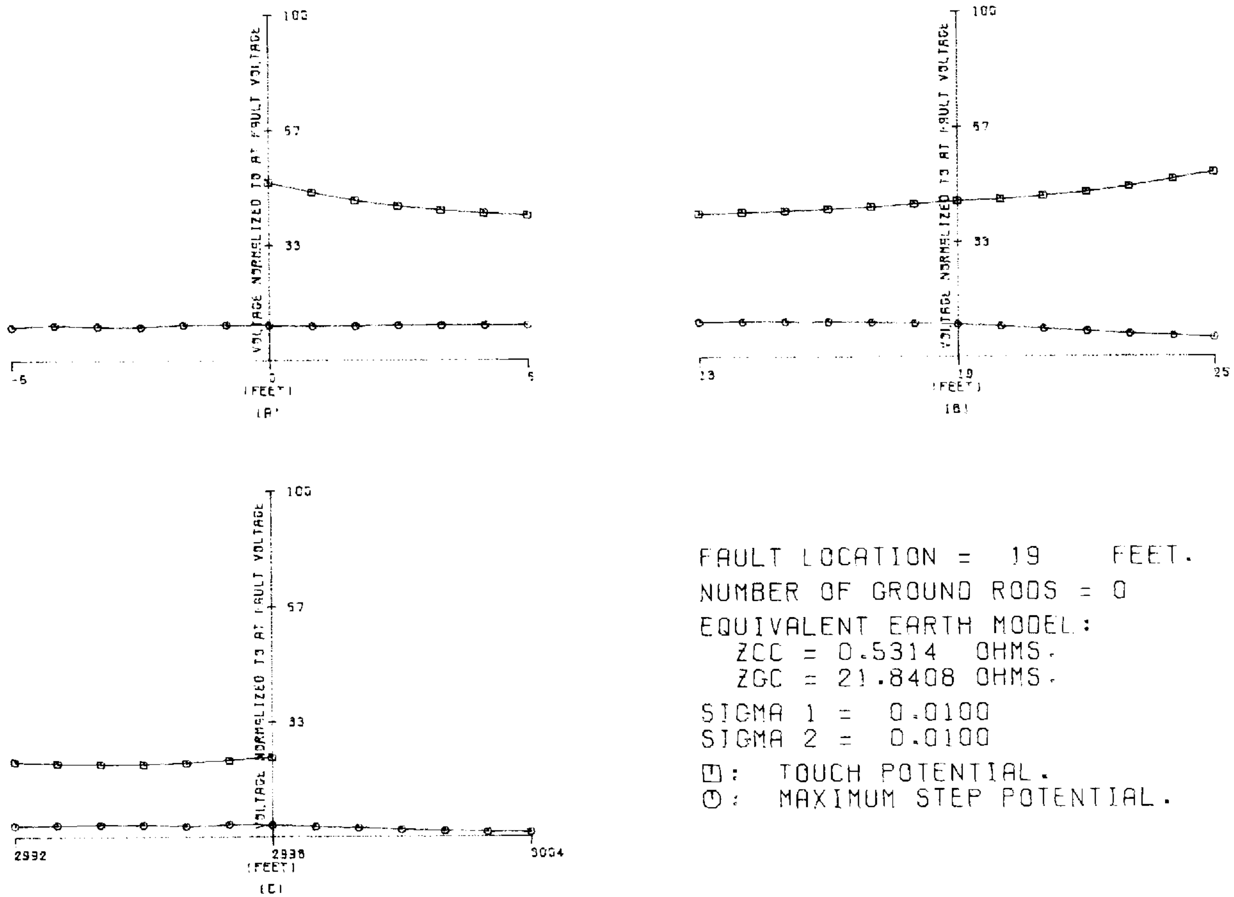


FIGURE B.68 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5314 OHMS.
ZGC = 21.8408 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.69 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

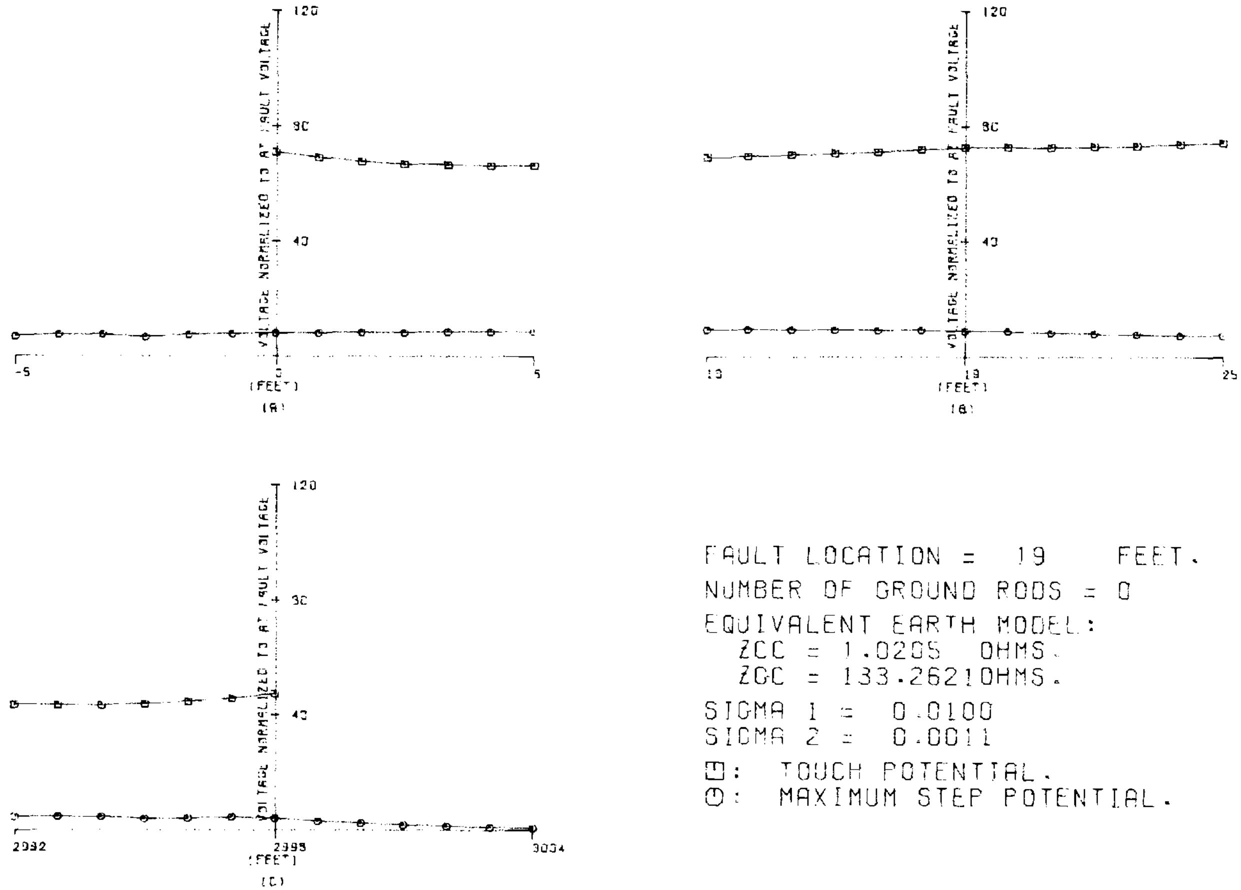
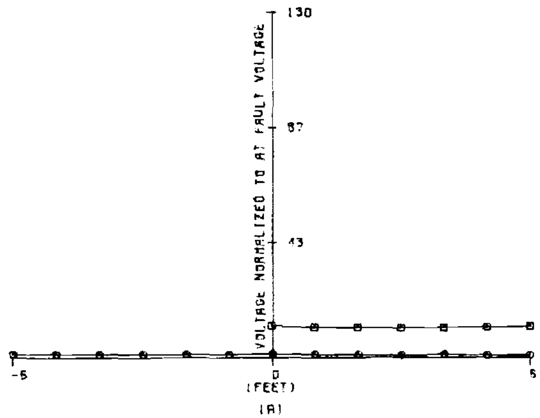
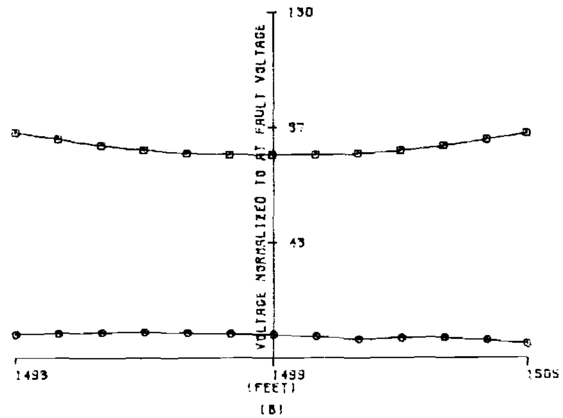
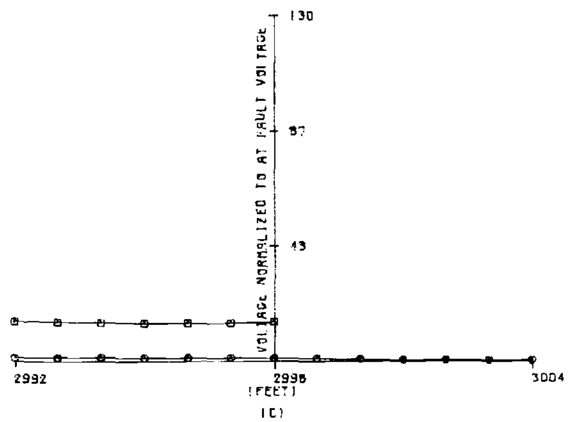


FIGURE B.70 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

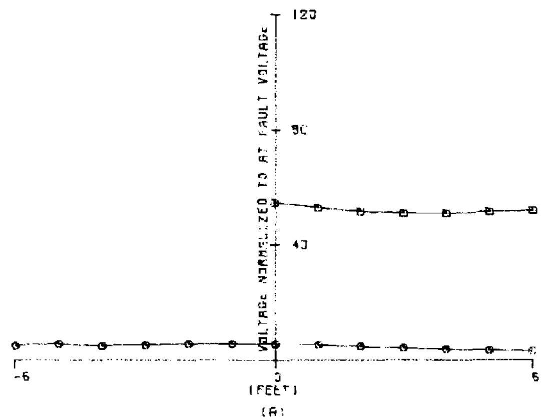


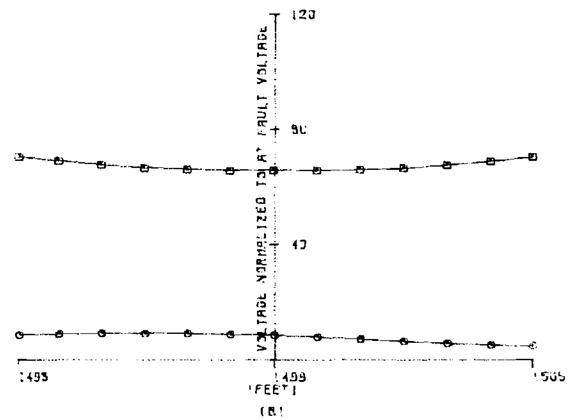


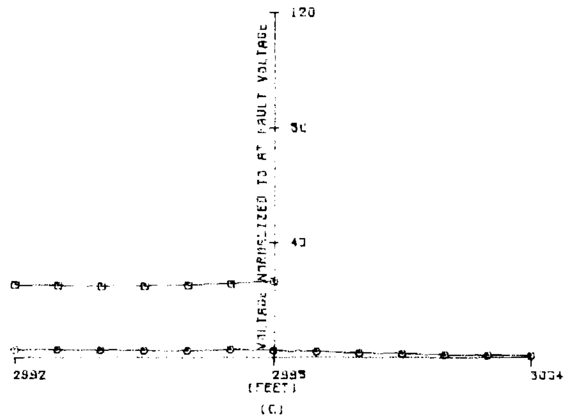


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.0799 OHMS.
ZGC = 5.9860 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.71 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.

NUMBER OF GROUND RODS = 0

EQUIVALENT EARTH MODEL:
ZCC = 0.1497 OHMS.
ZGC = 11.6022 OHMS.

SIGMA 1 = 0.1000
SIGMA 2 = 0.0200

□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.72 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

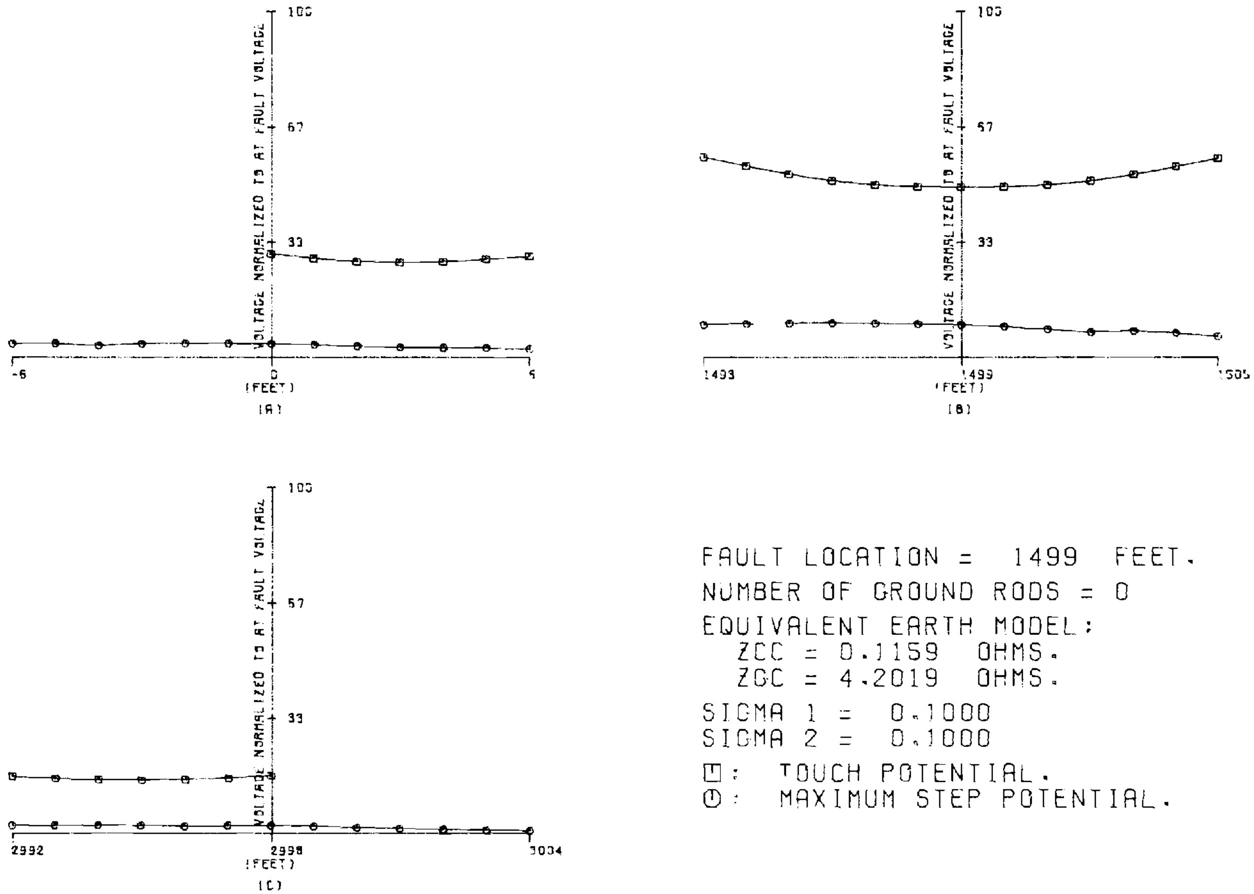


FIGURE B.73 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

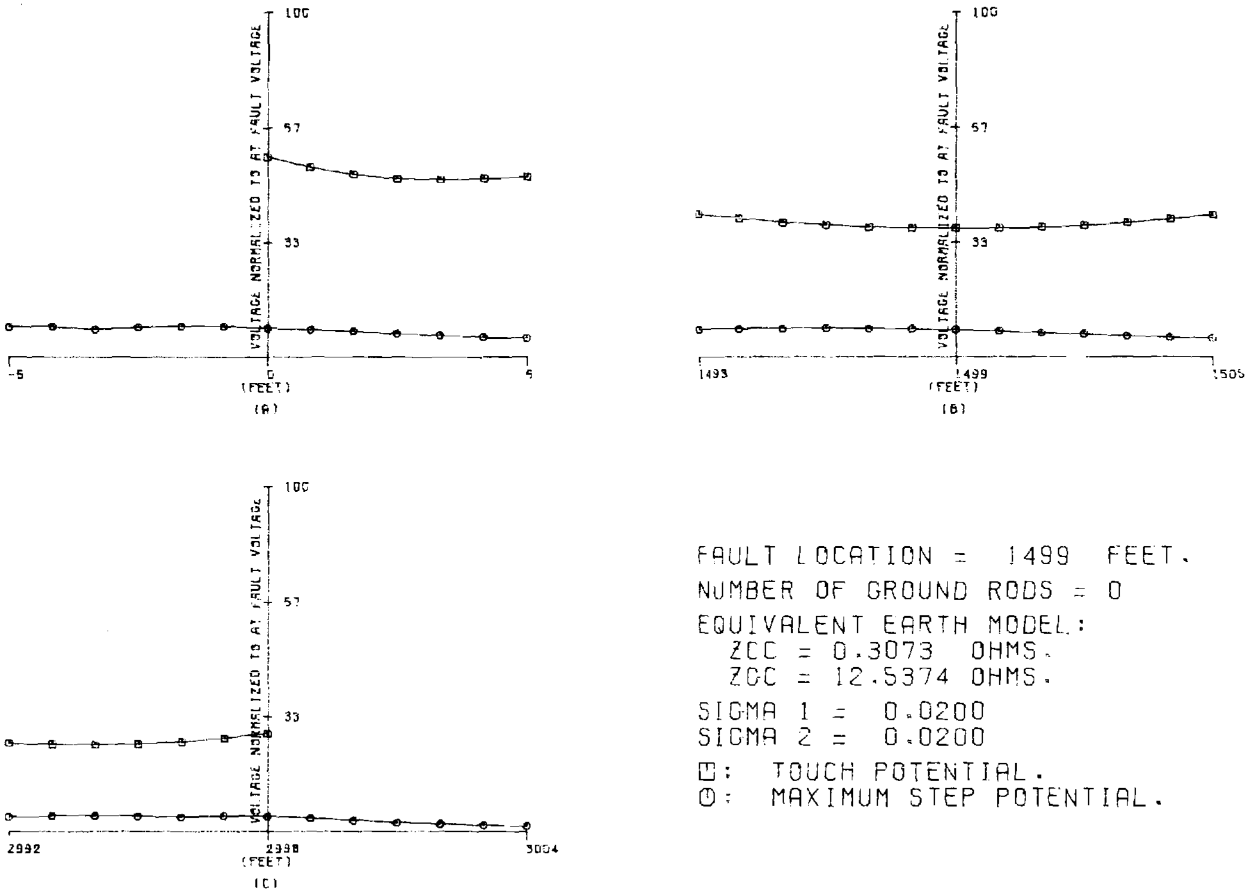
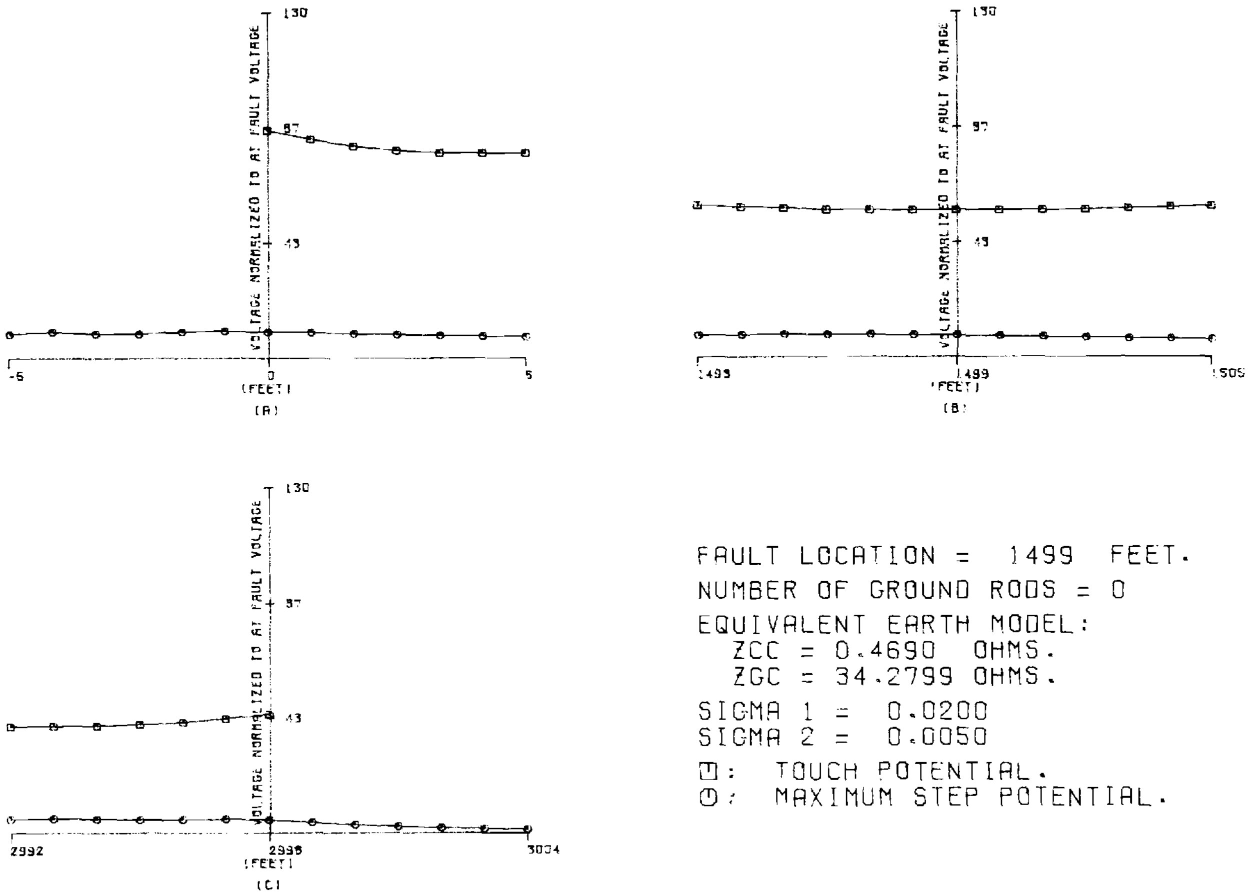


FIGURE B.74 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.4690 OHMS.
ZGC = 34.2799 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.75 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

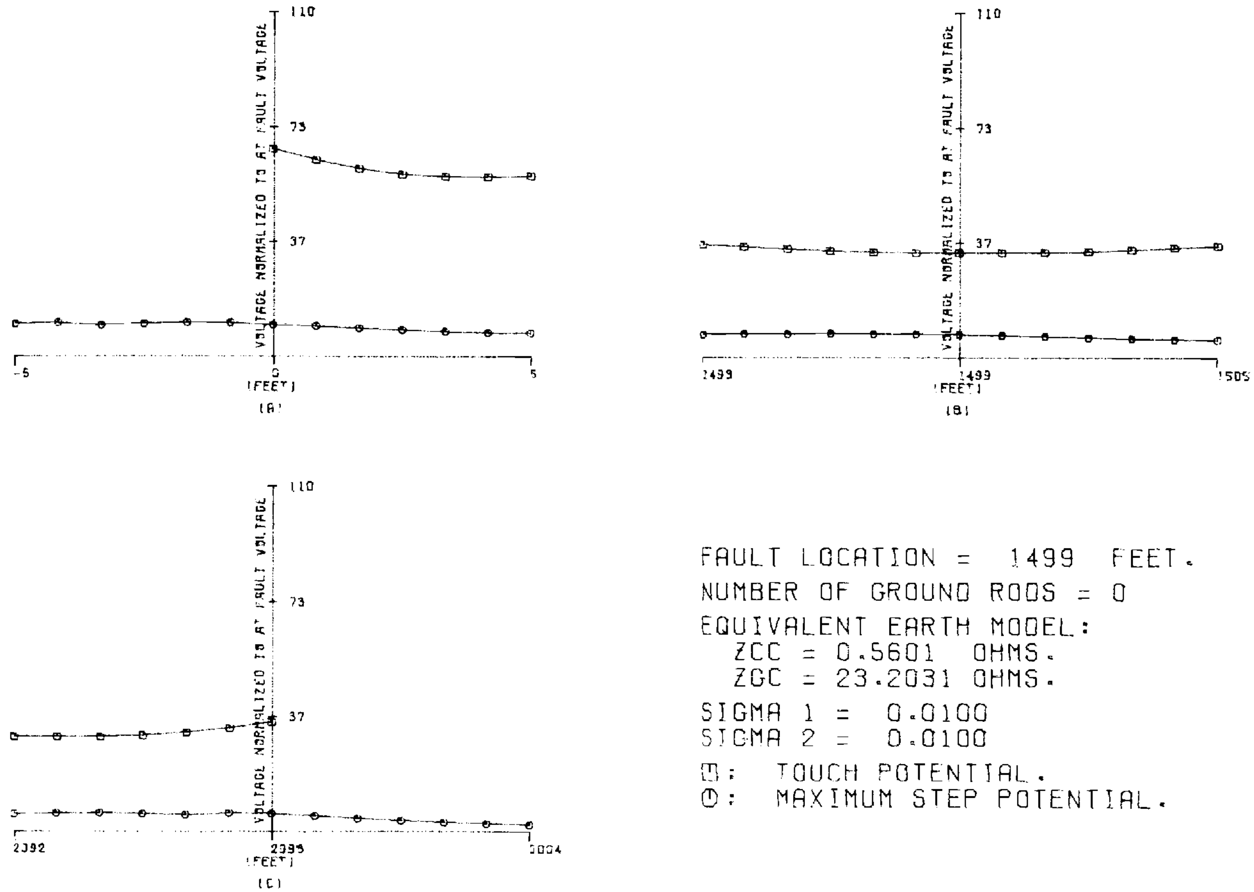
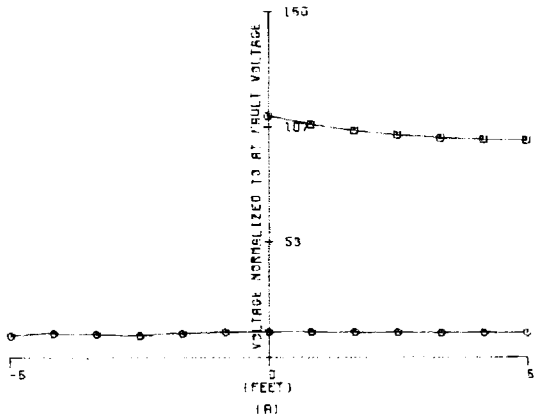
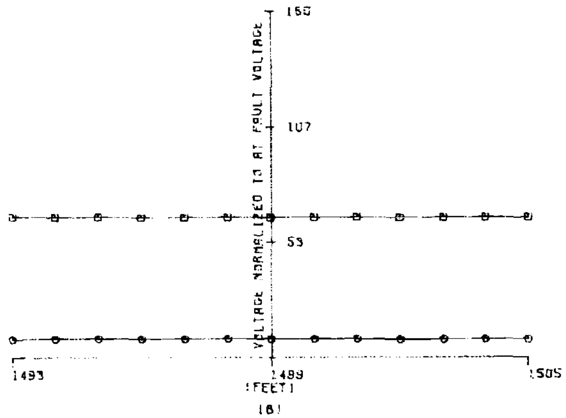
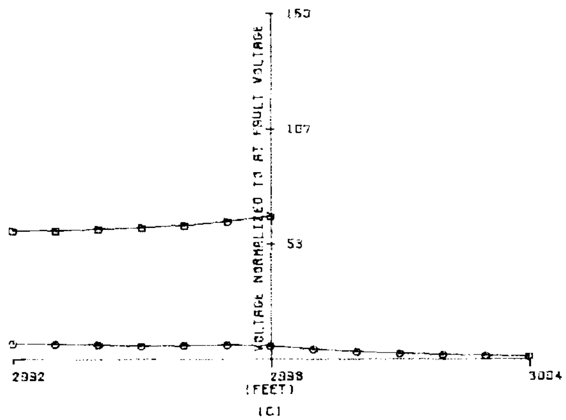


FIGURE B.76 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 1.3901 OHMS.
ZGC = 168.9534OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.77 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

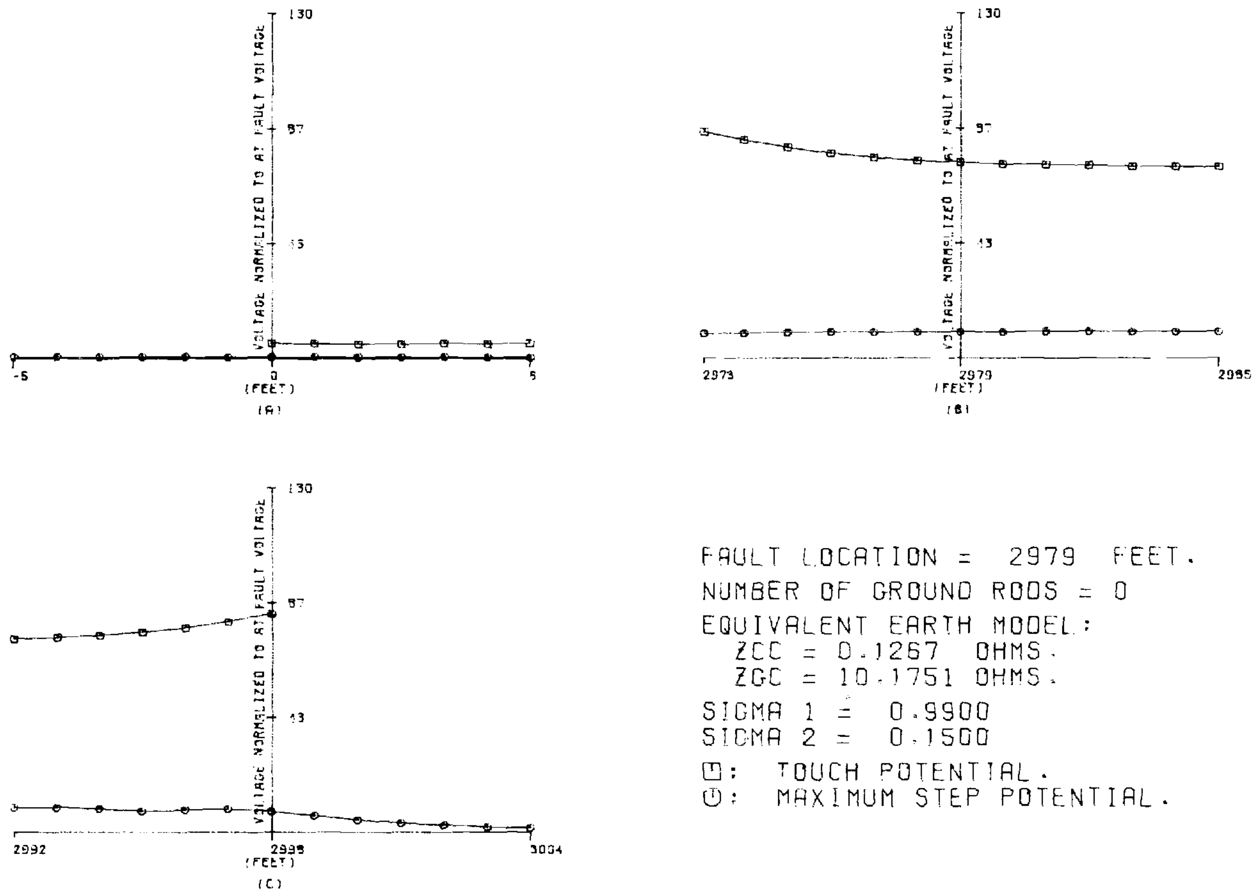
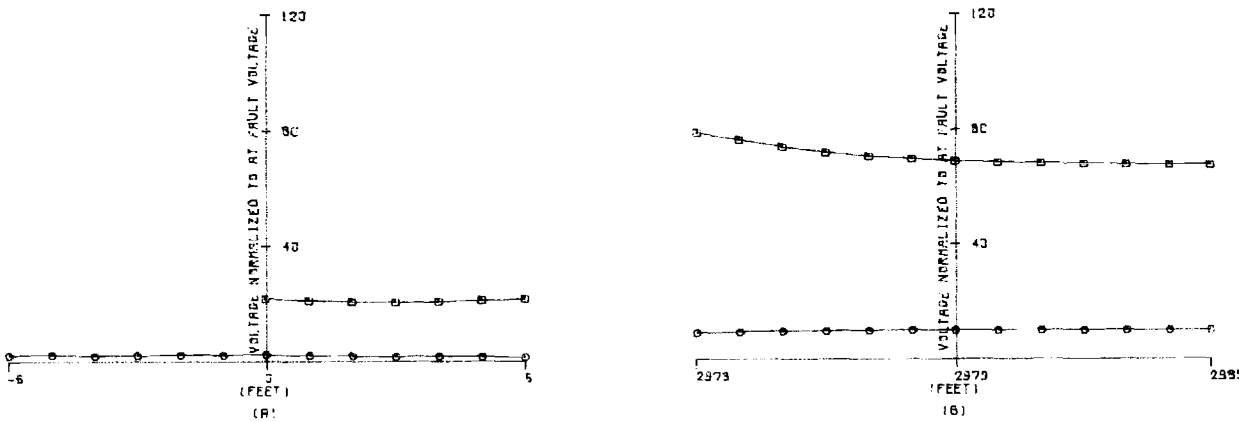
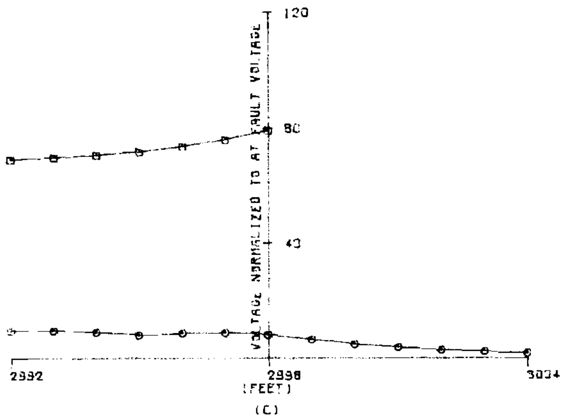


FIGURE B.78 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.2751 OHMS.
ZGC = 21.7024 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.79 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

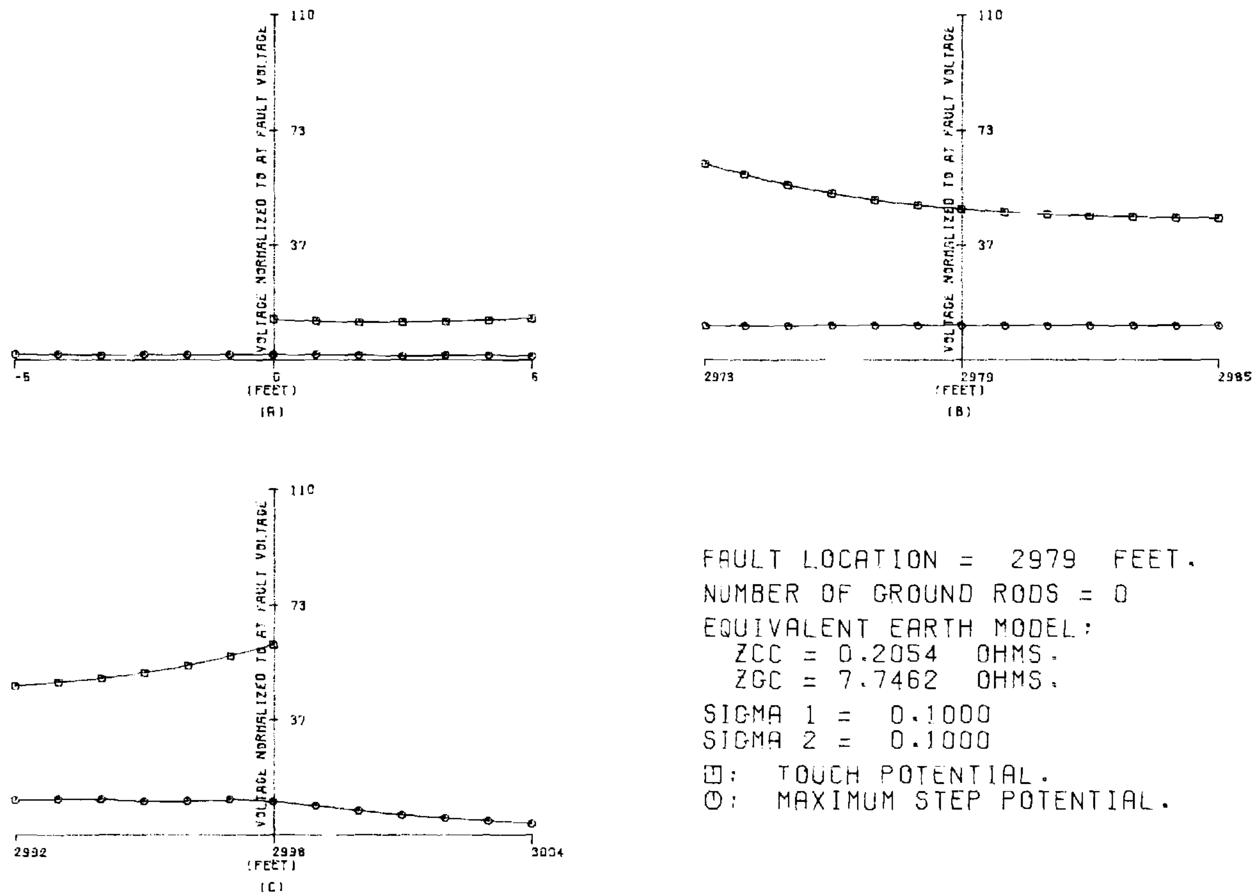
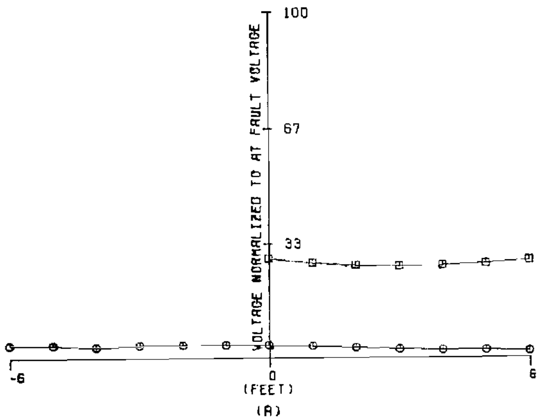
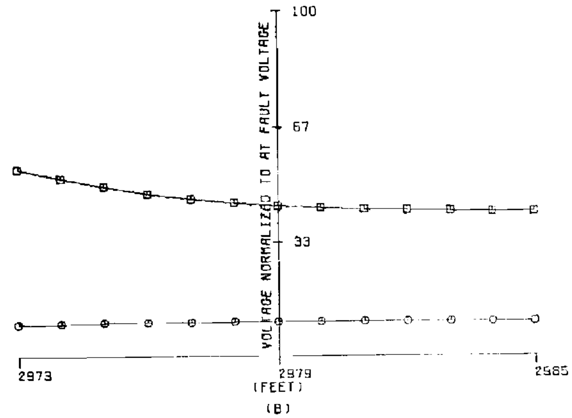
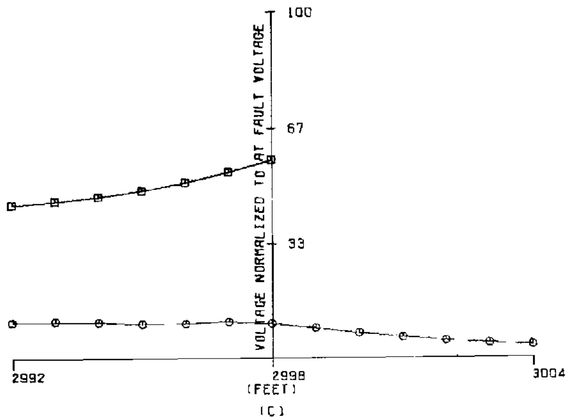


FIGURE B.80 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

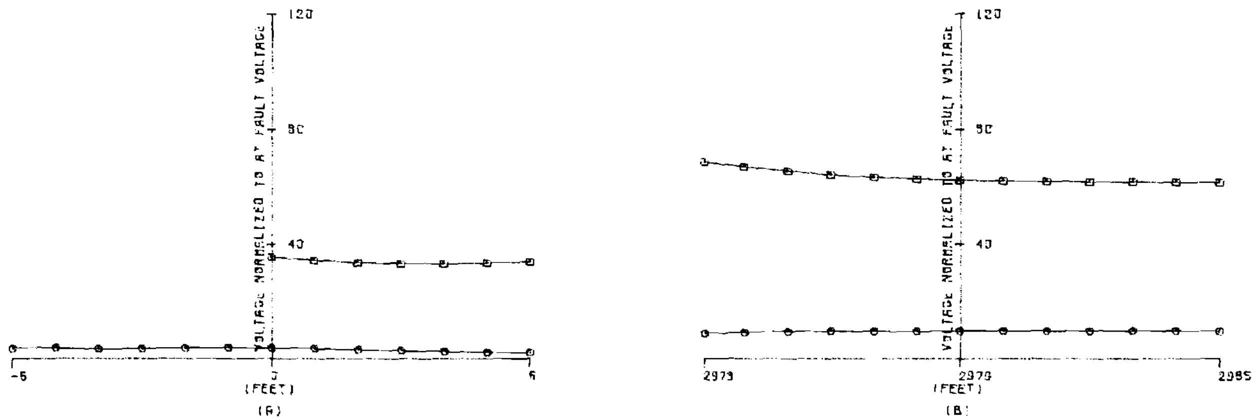


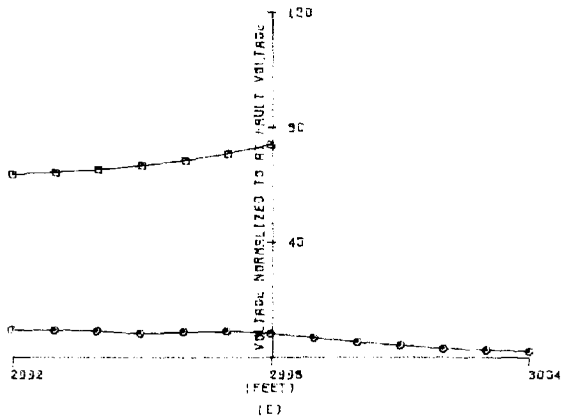




FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5940 OHMS.
ZGC = 22.3715 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

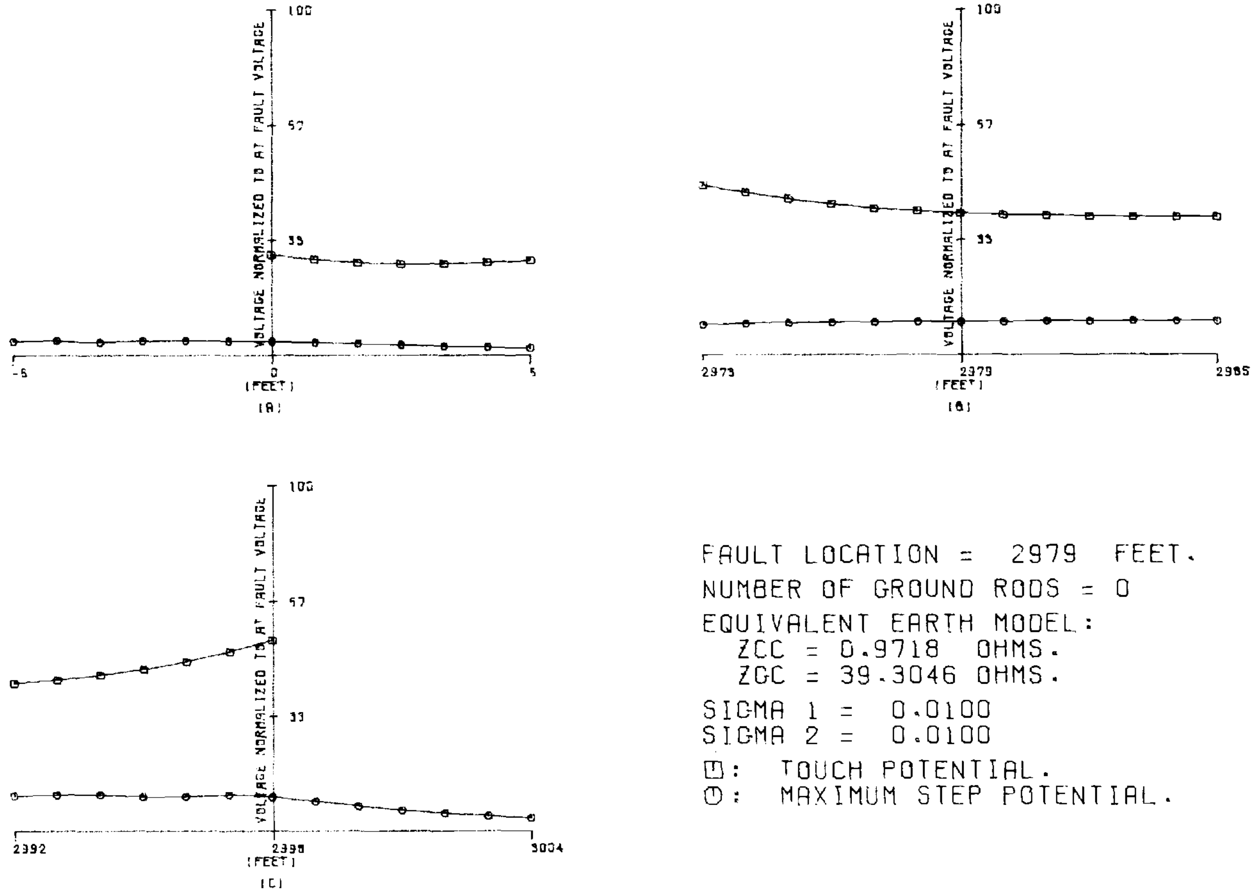
FIGURE B.81 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.8203 OHMS.
ZGC = 58.5833 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.82 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.9718 OHMS.
ZGC = 39.3046 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.83 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

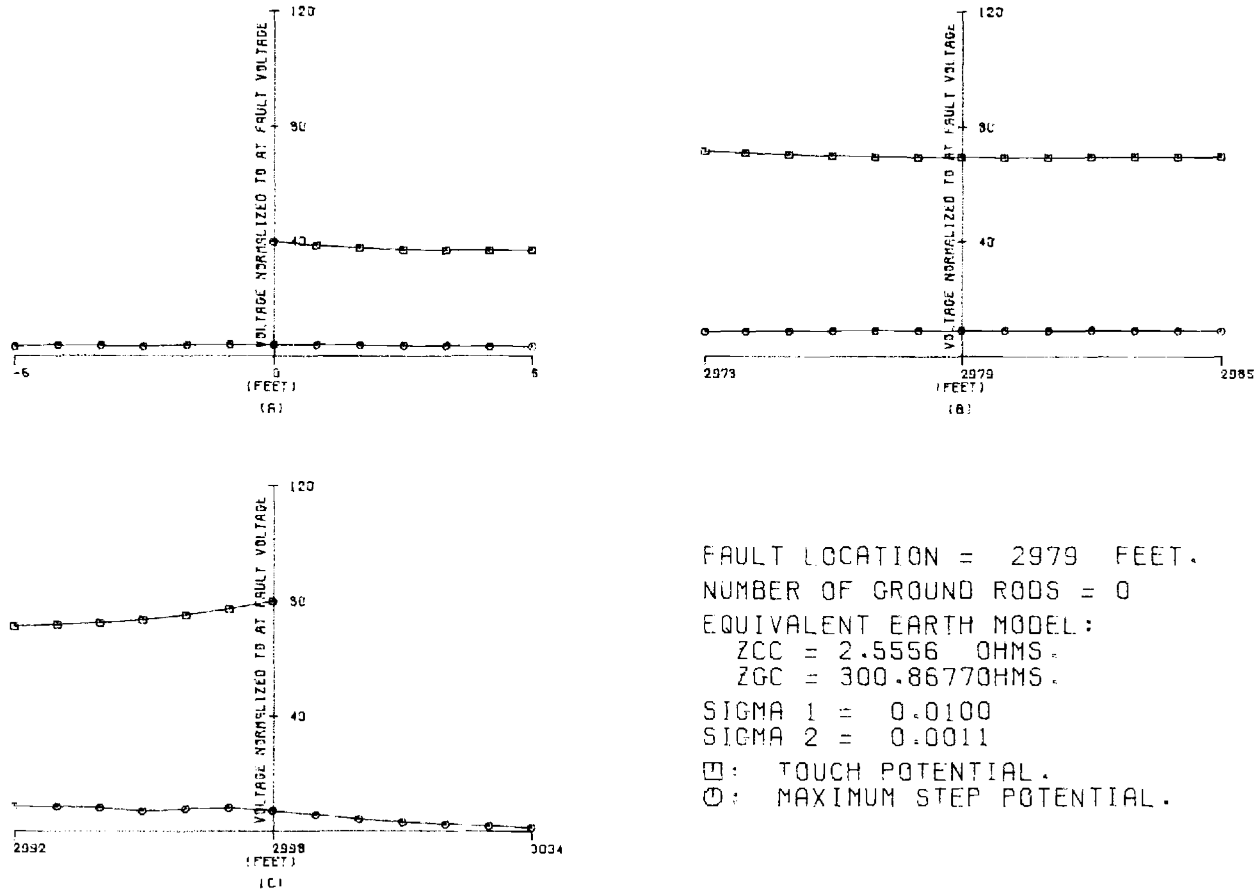


FIGURE B.84 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABlE END.

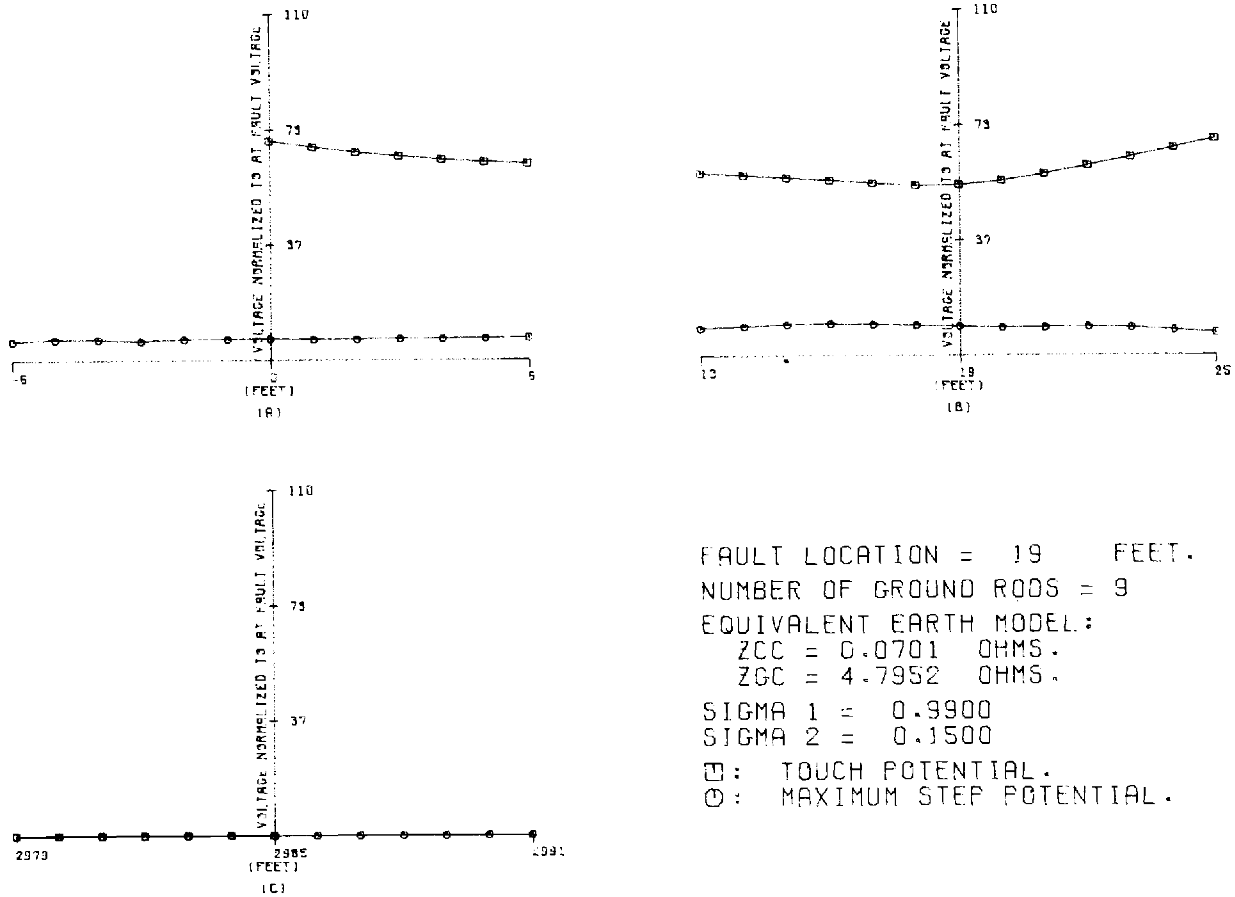


FIGURE B.85 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

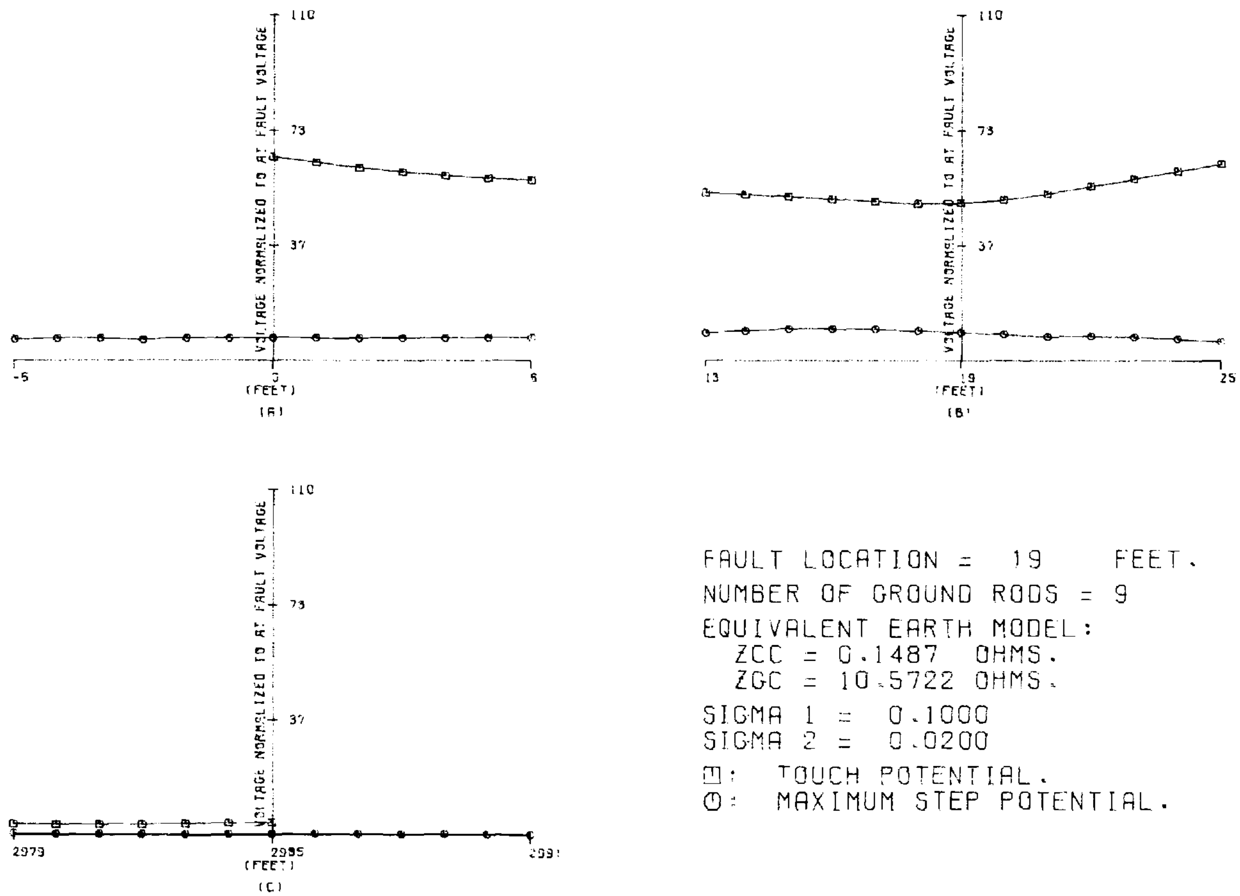
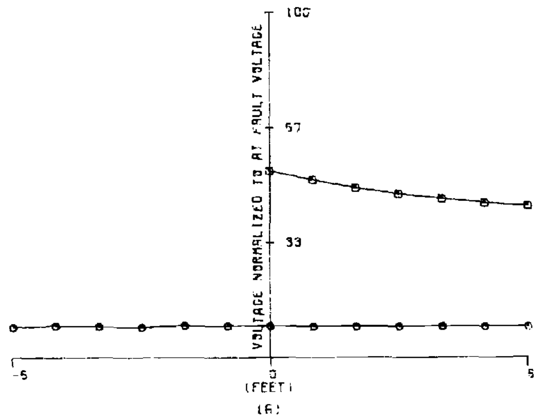
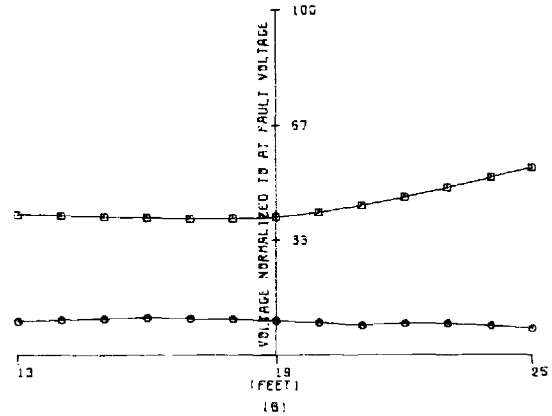
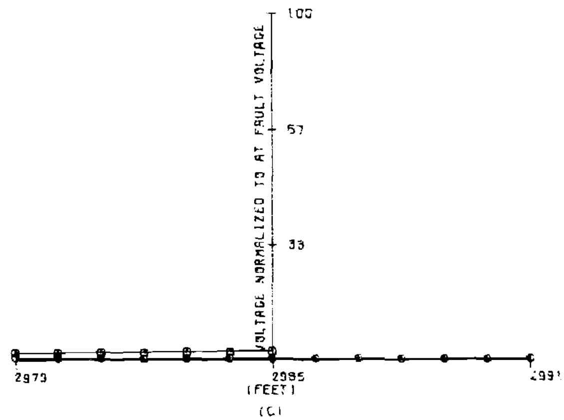


FIGURE B.86 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1245 OHMS.
ZGC = 4.5757 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.87 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

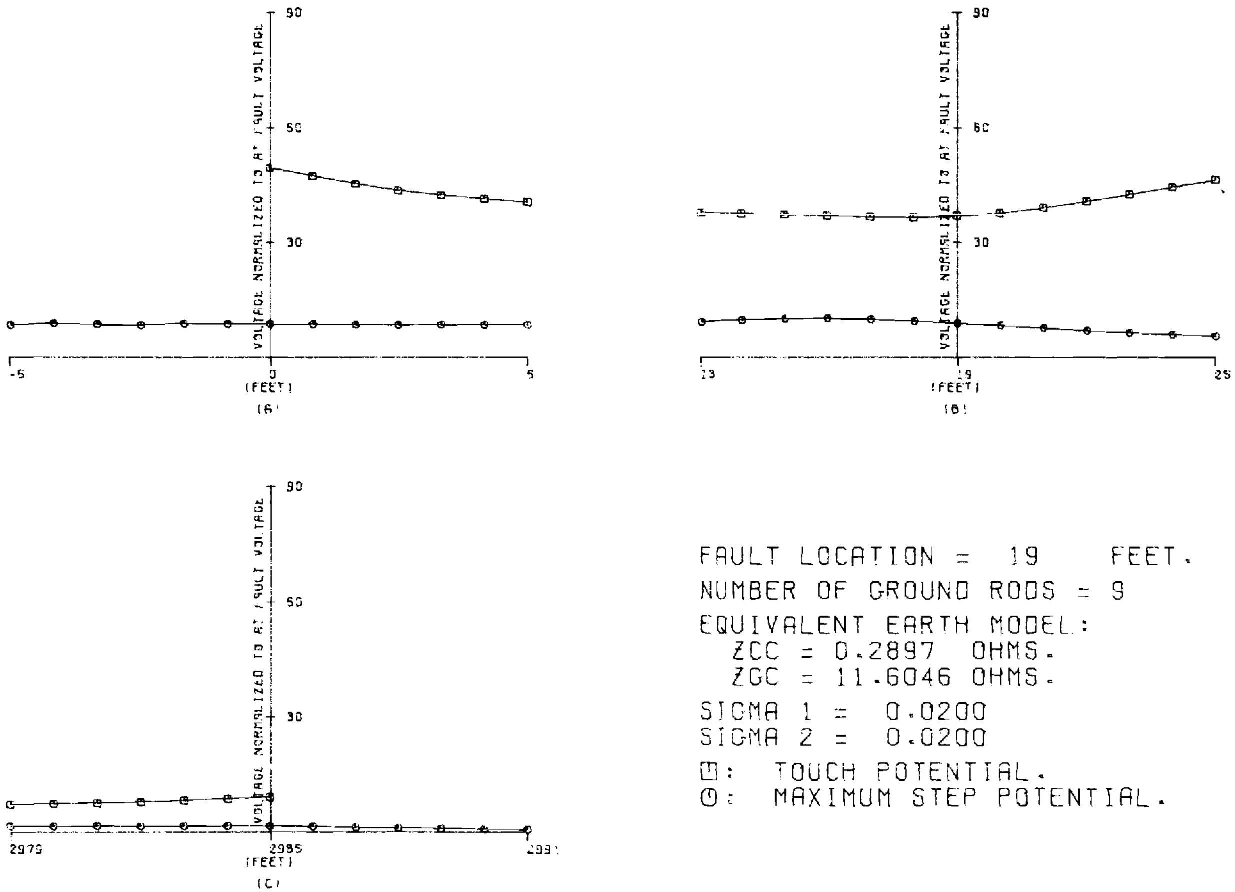
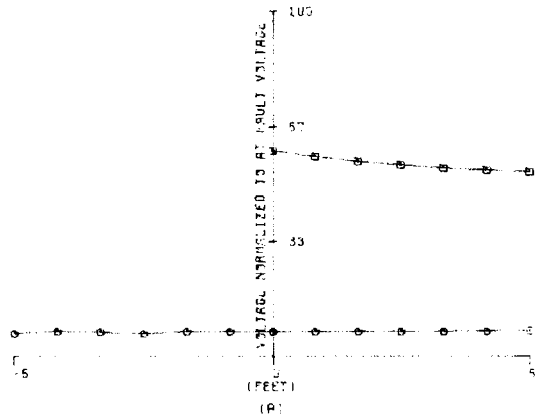
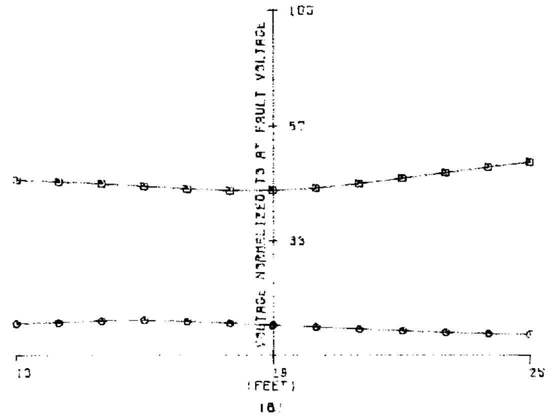
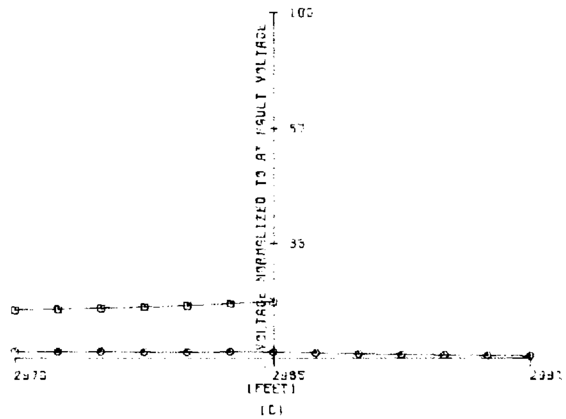


FIGURE B.88 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.3757 OHMS.
ZCC = 29.0048 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.89 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

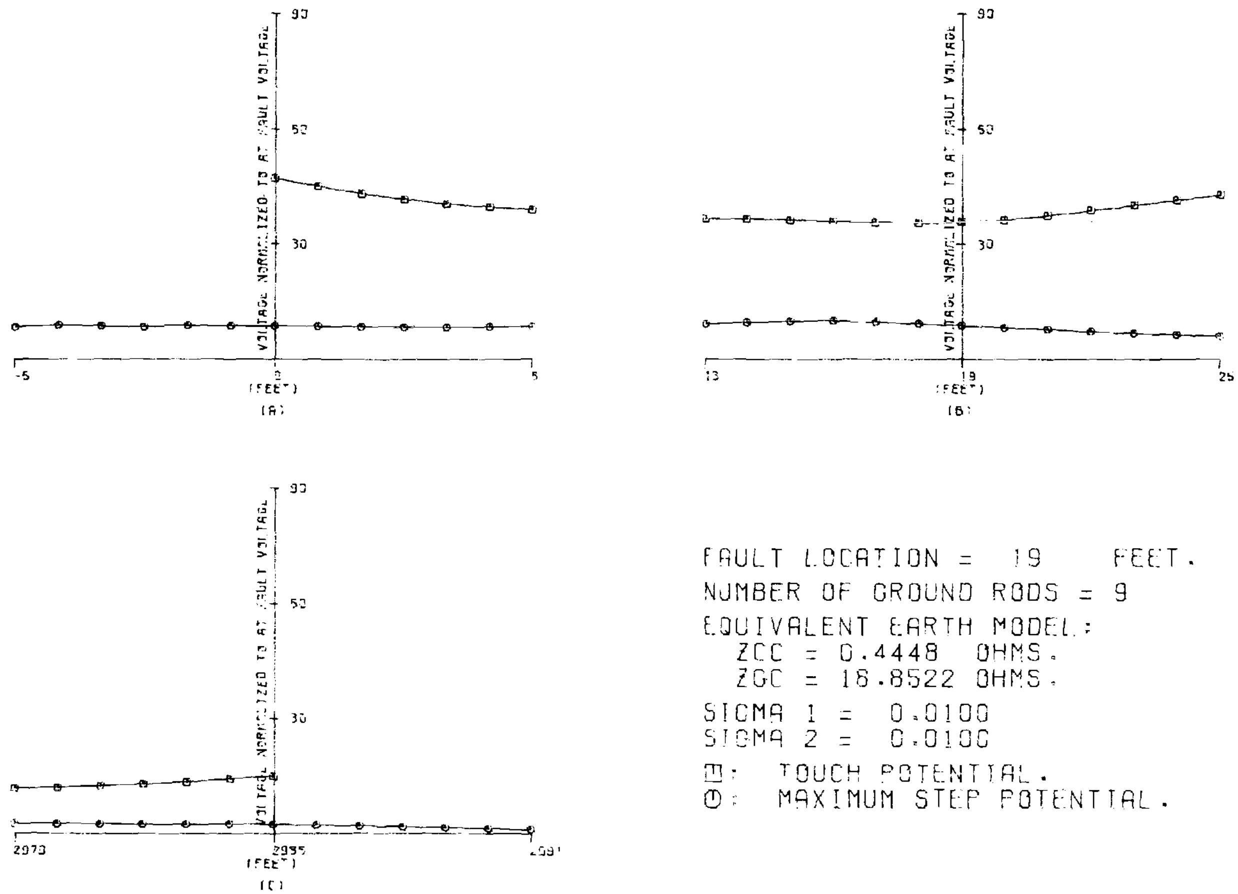
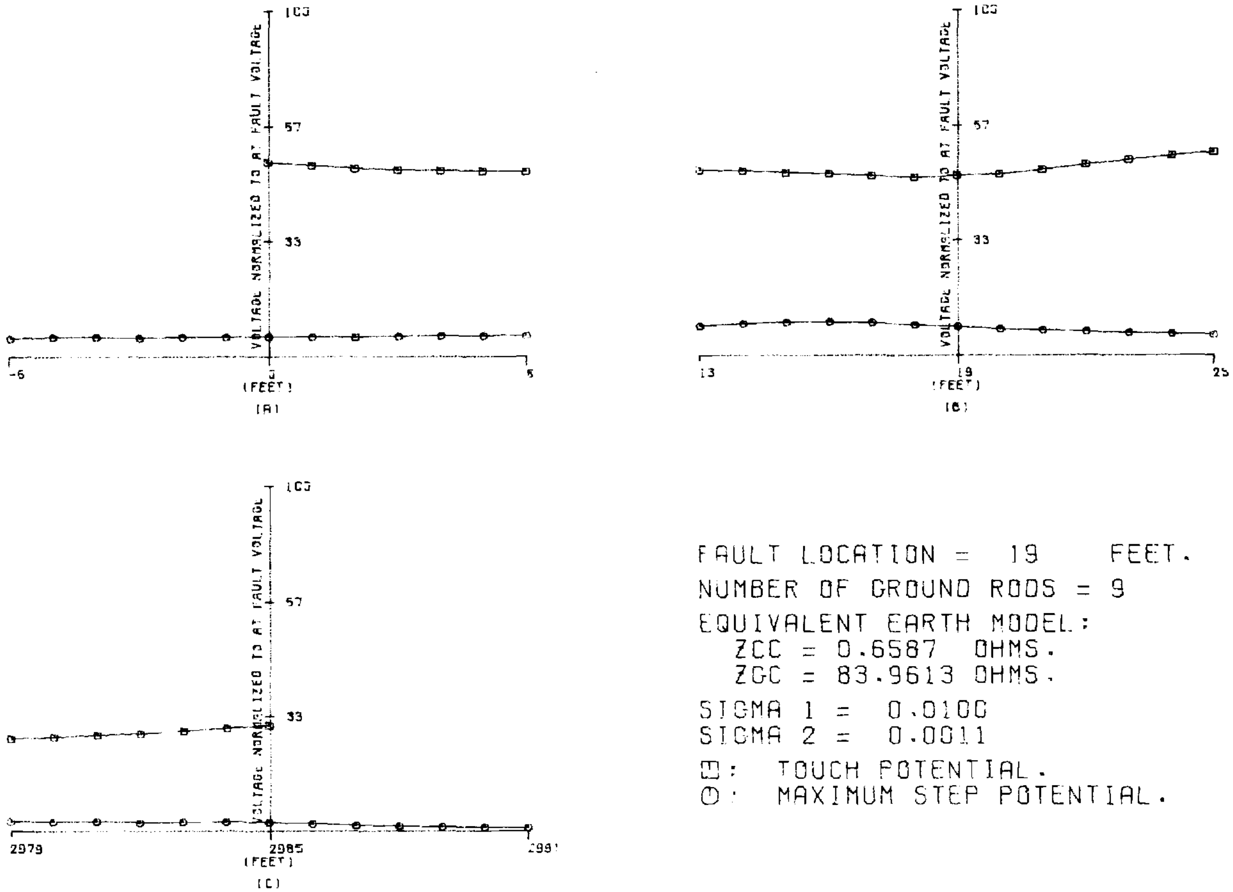
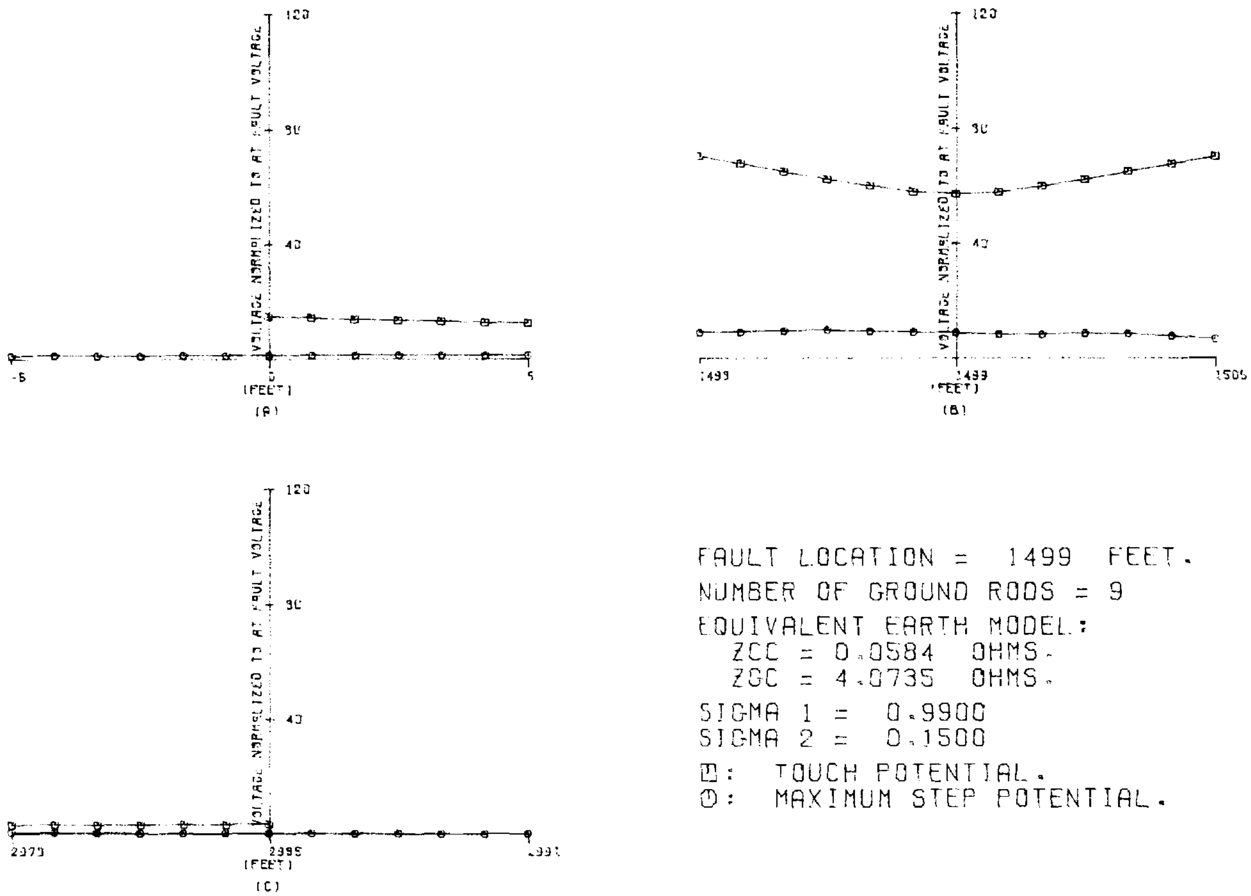


FIGURE B.90 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.6587 OHMS.
ZGC = 83.9613 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
▢: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.91 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.0584 OHMS.
ZGC = 4.0735 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.92 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

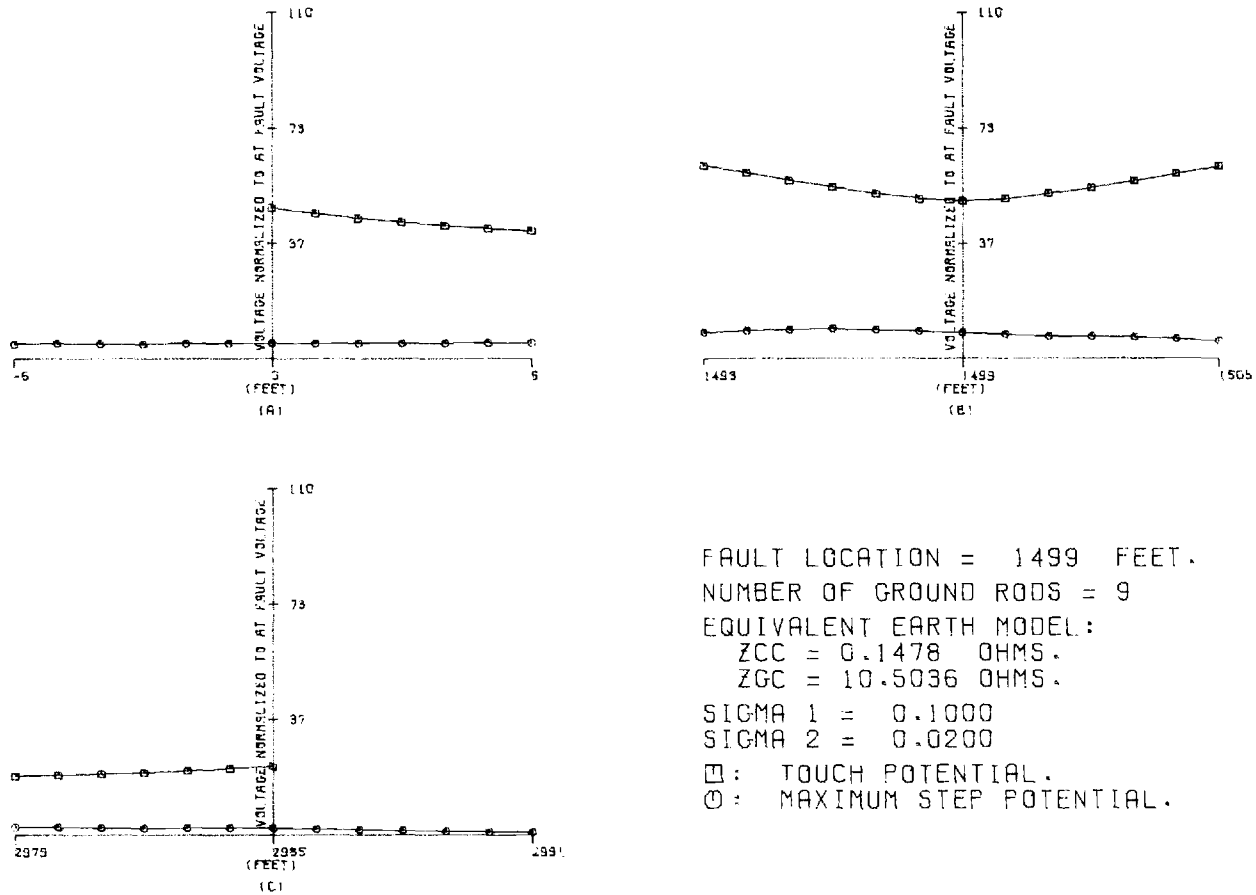


FIGURE B.93 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

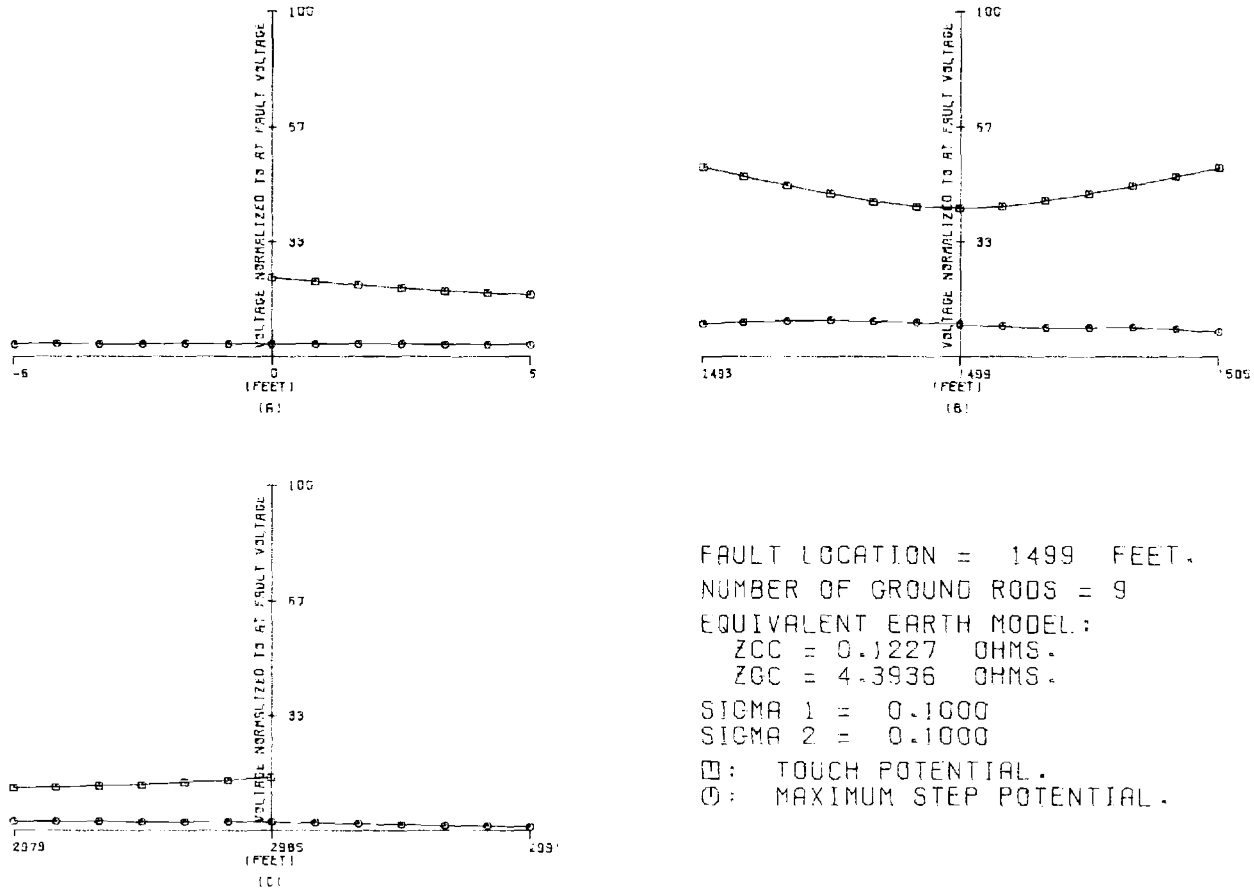


FIGURE B.94 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

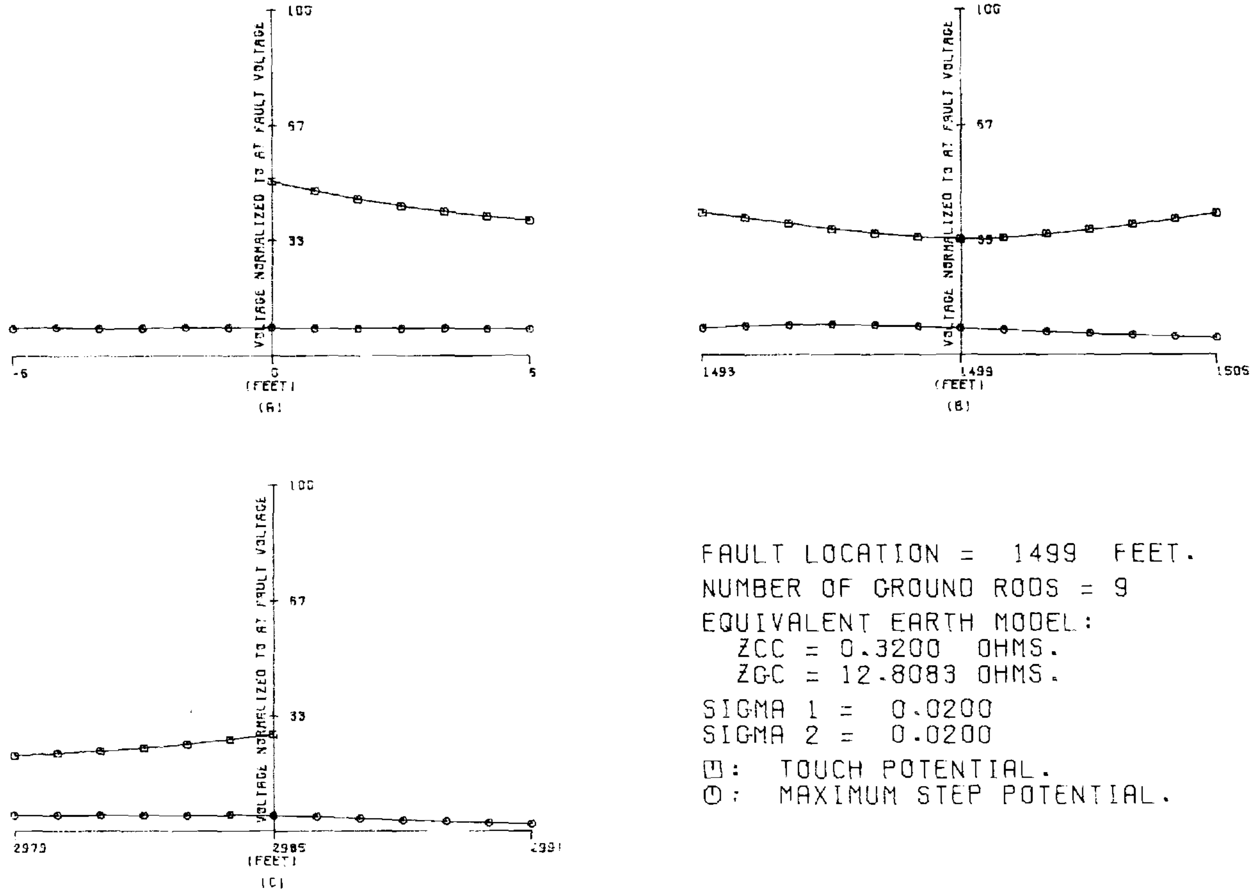


FIGURE B.95 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

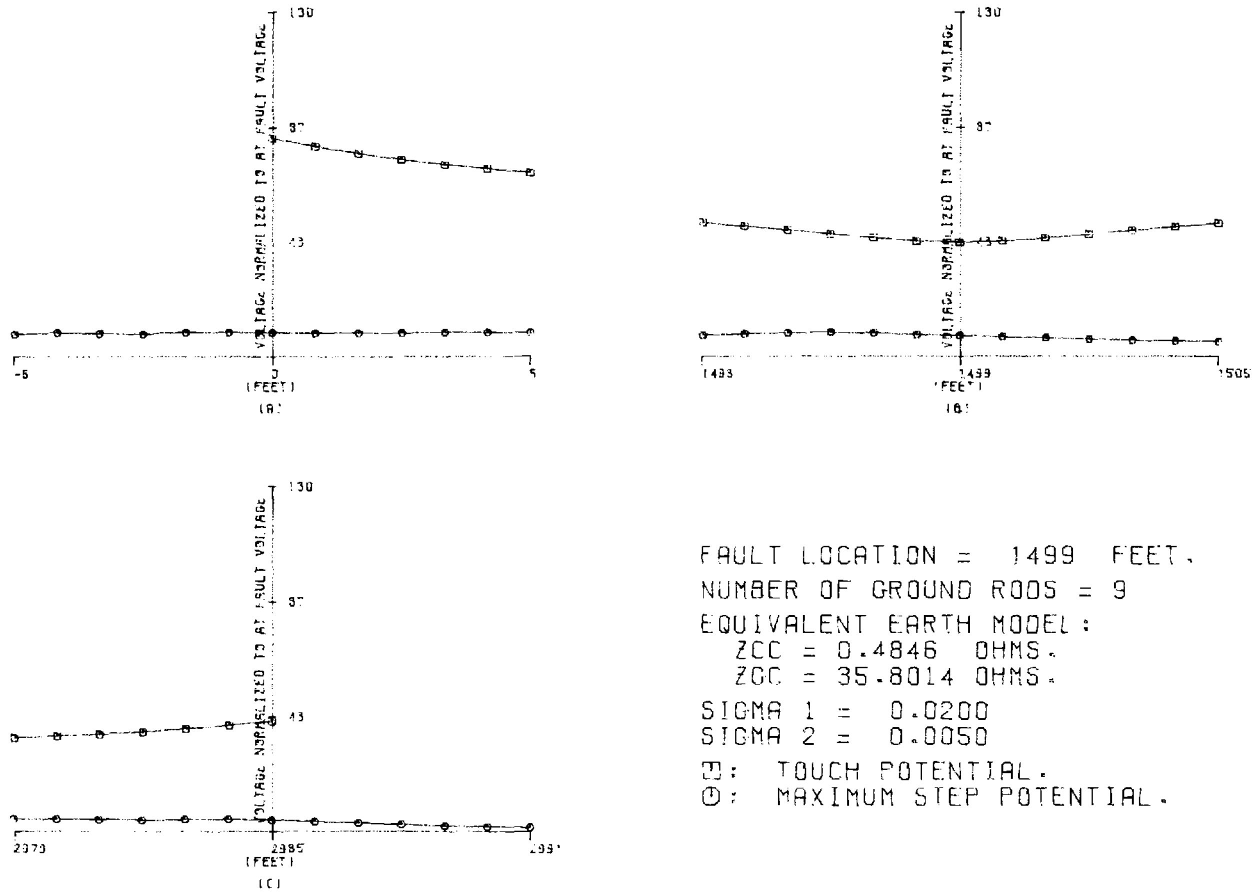


FIGURE B.96 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

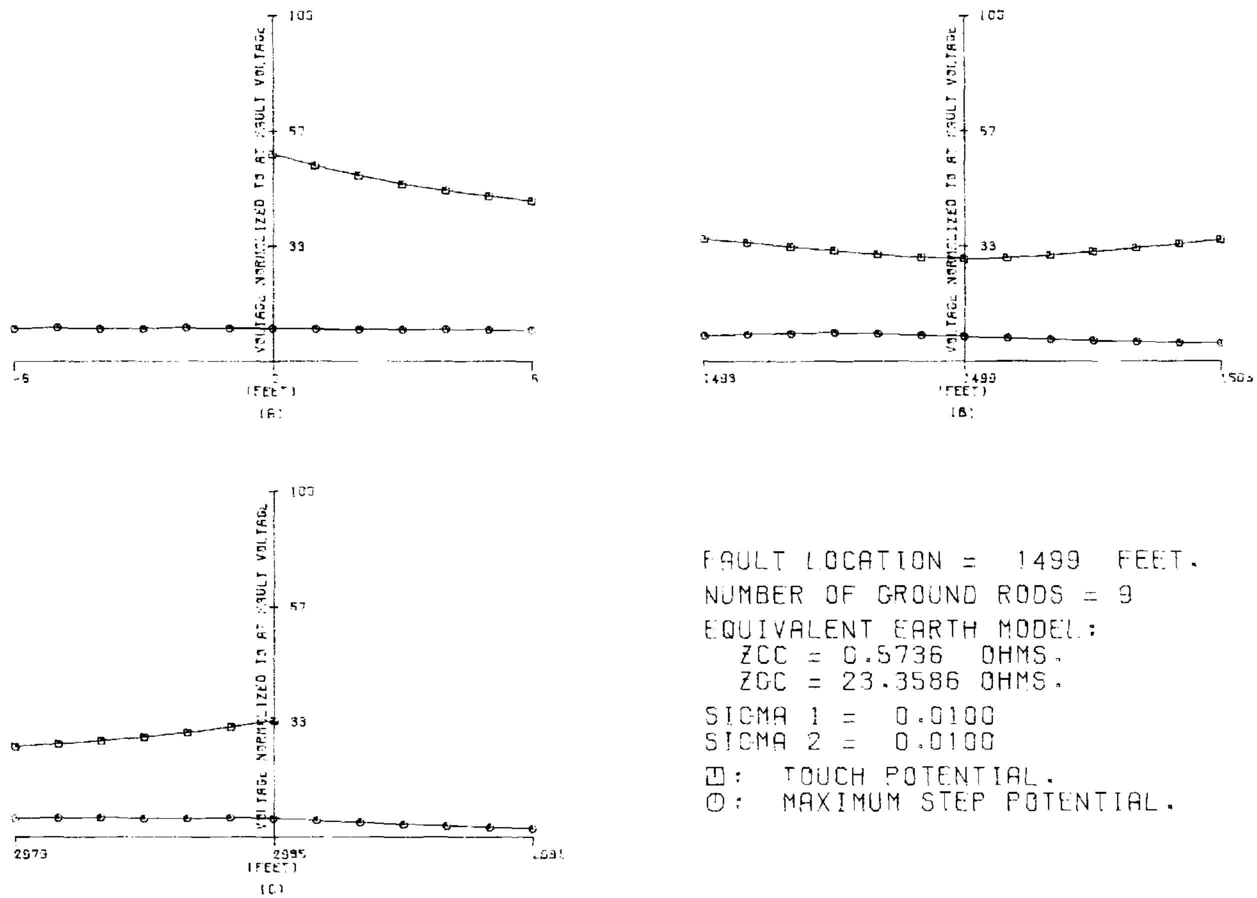


FIGURE B.97 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

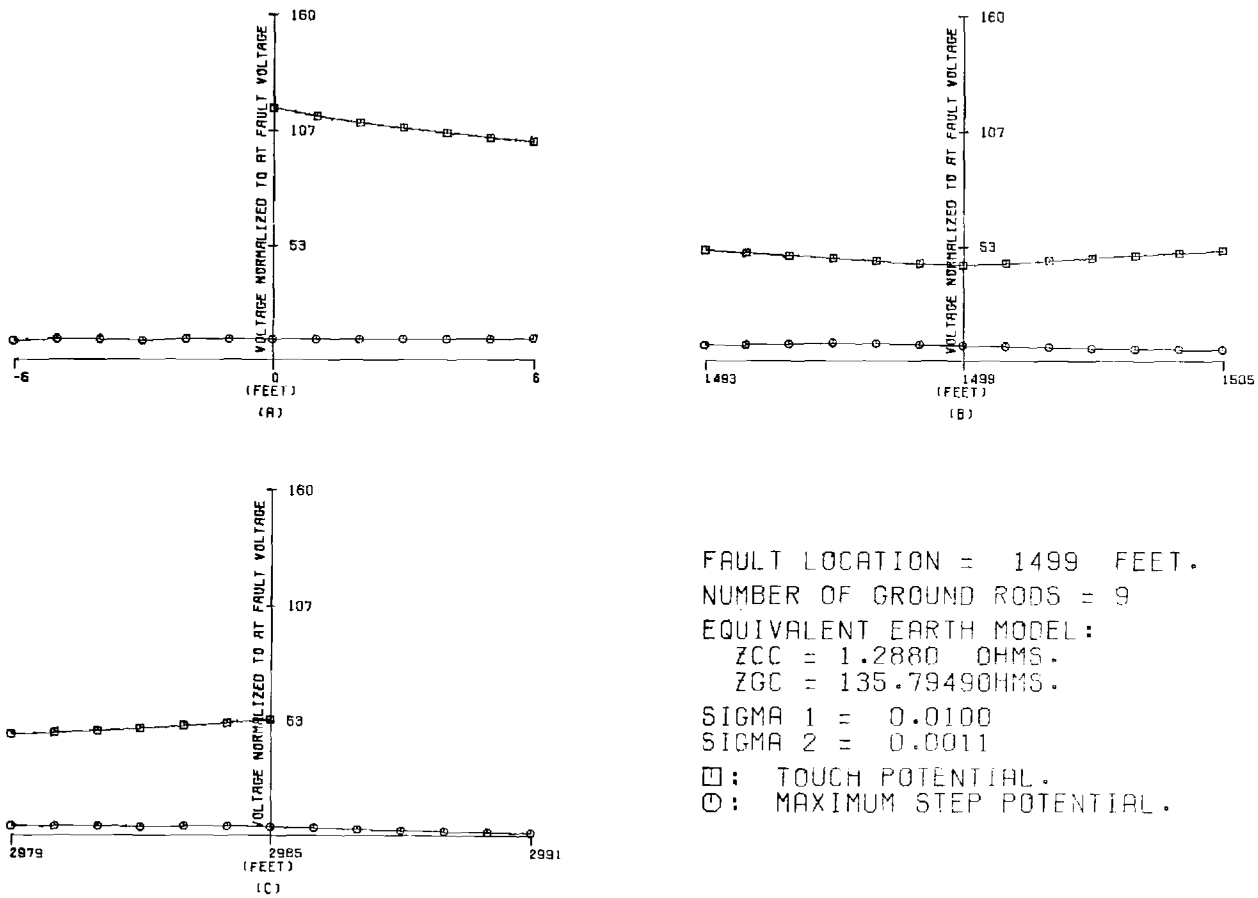
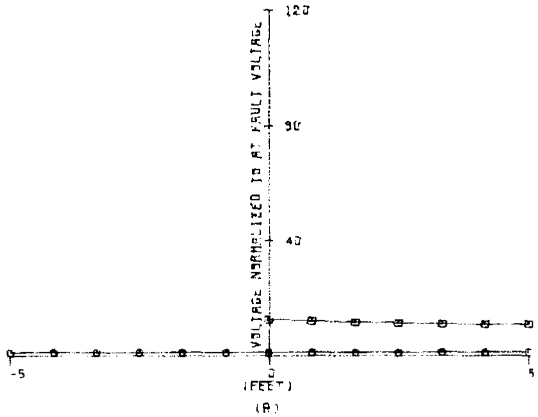
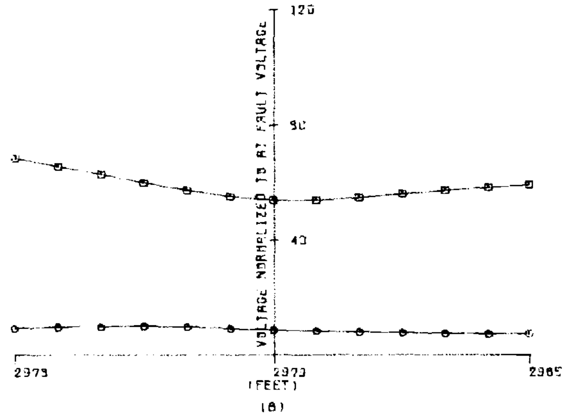
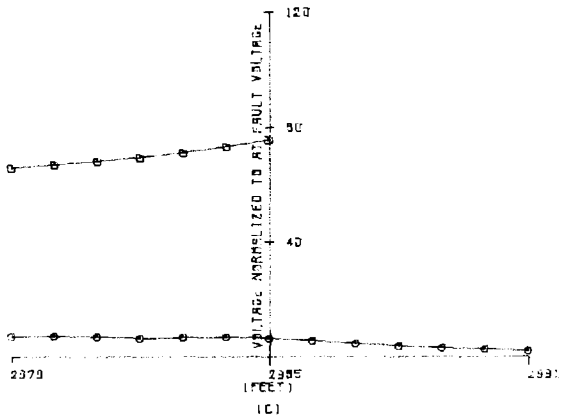


FIGURE B.98 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 2979 FEET.

NUMBER OF GROUND RODS = 9

EQUIVALENT EARTH MODEL:
ZCC = 0.0614 OHMS.
ZGC = 4.4441 OHMS.

SIGMA 1 = 0.9900
SIGMA 2 = 0.1500

□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.99 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

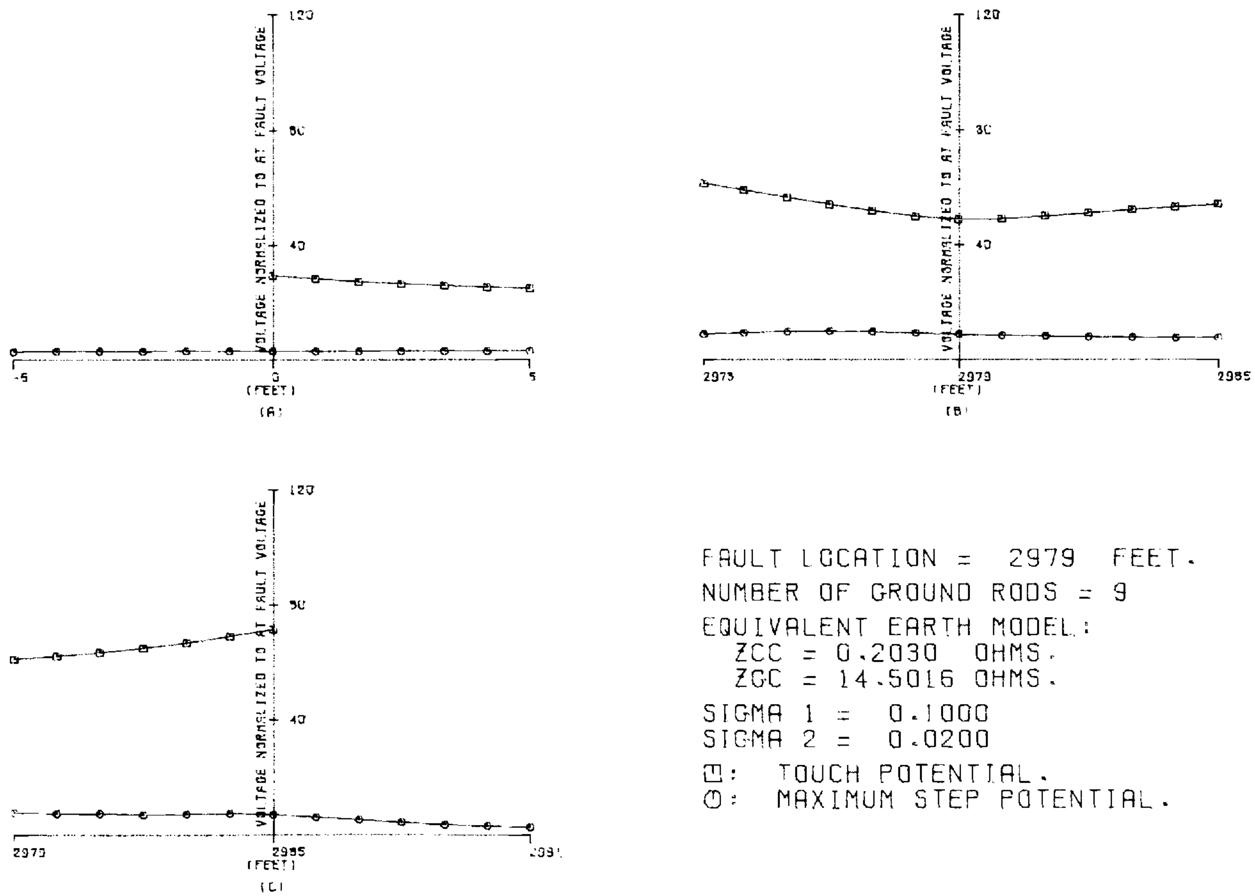


FIGURE B.100 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

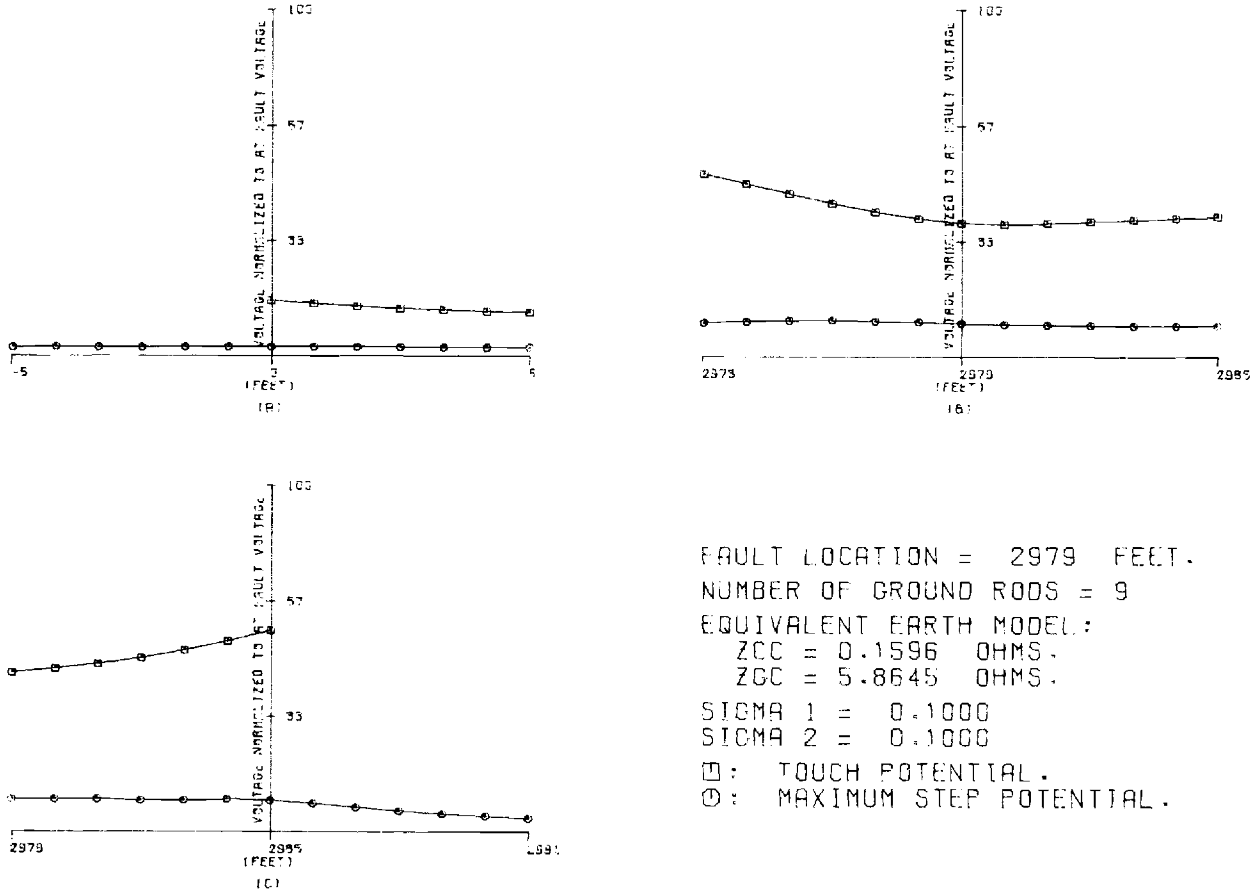


FIGURE B.101 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

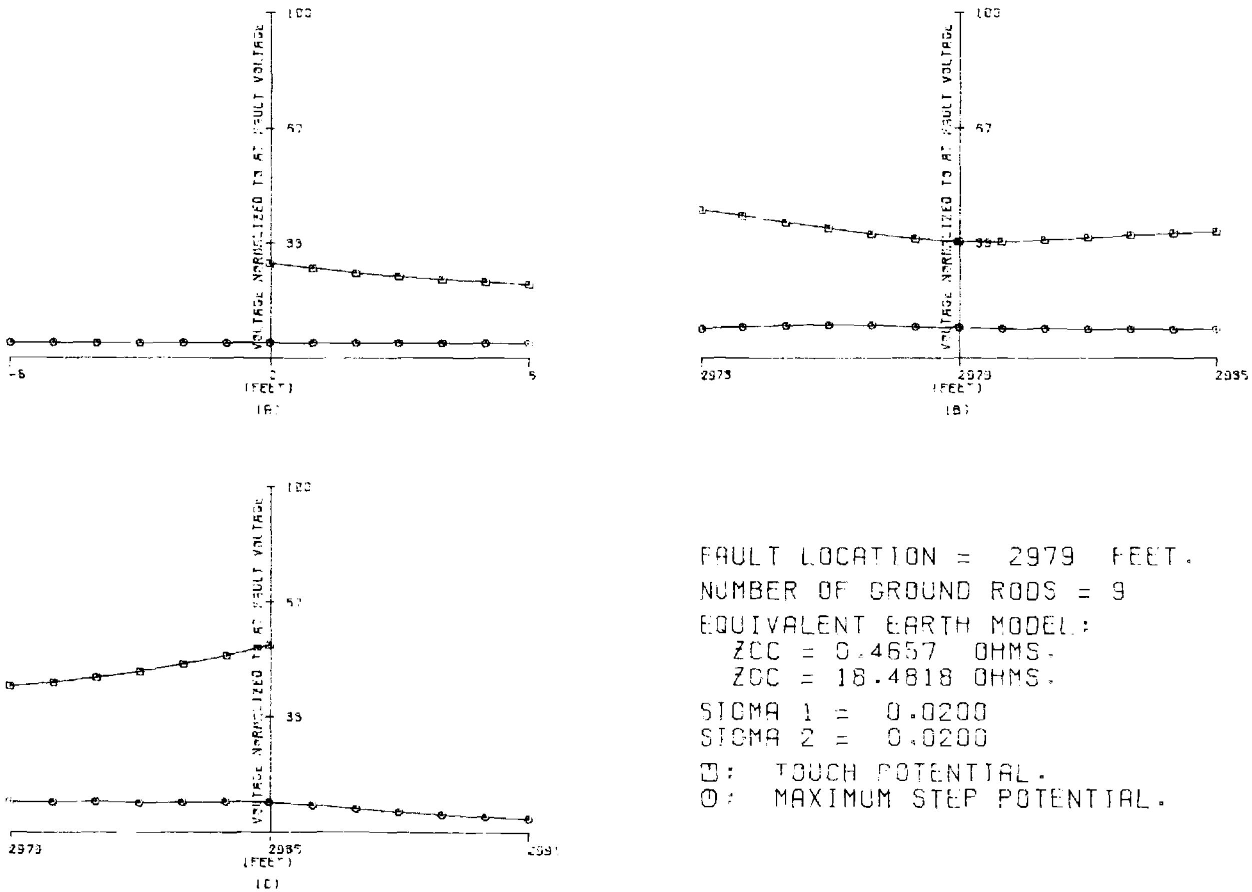


FIGURE B.102 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

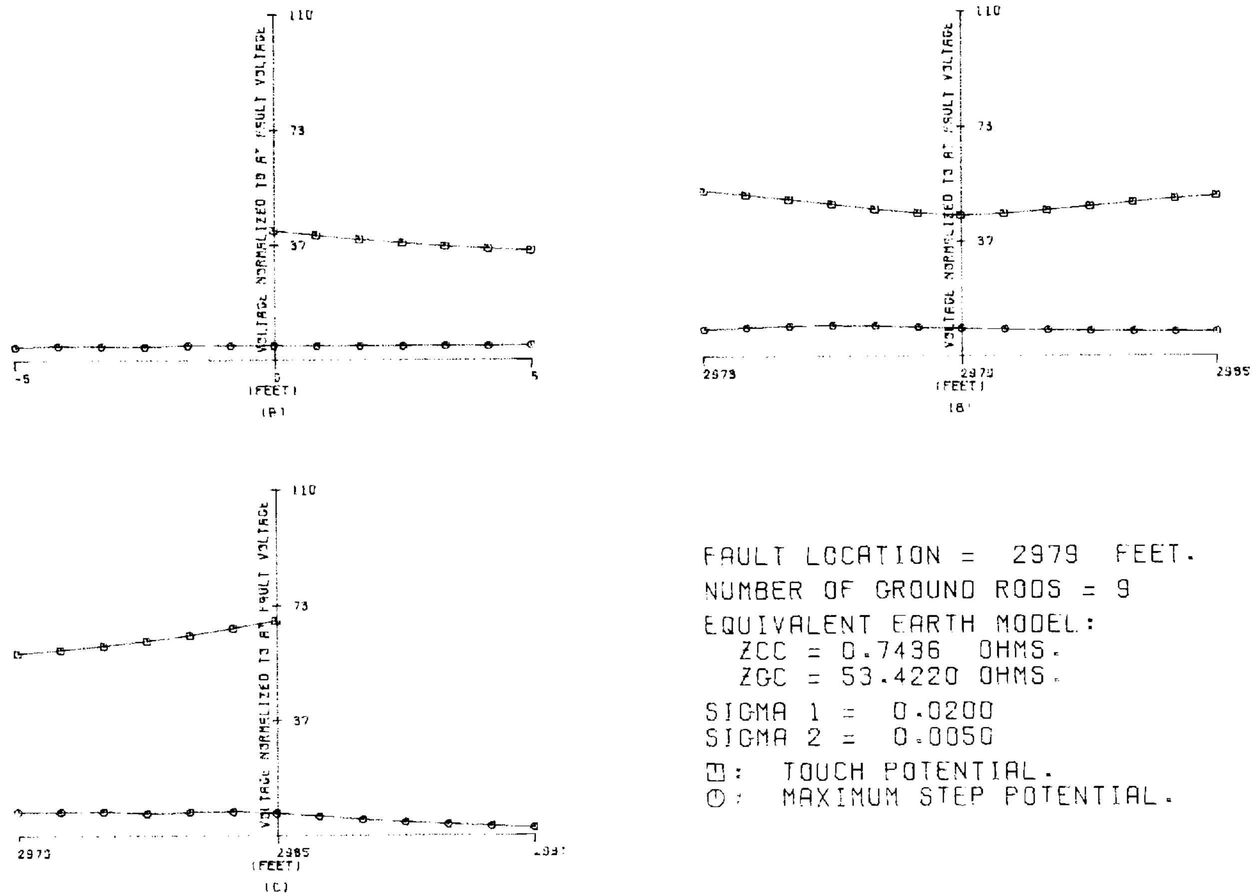
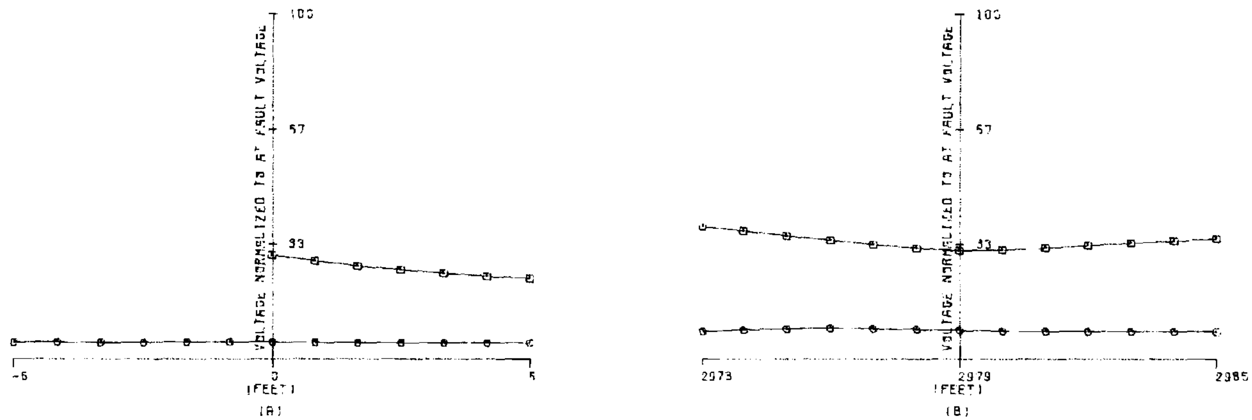
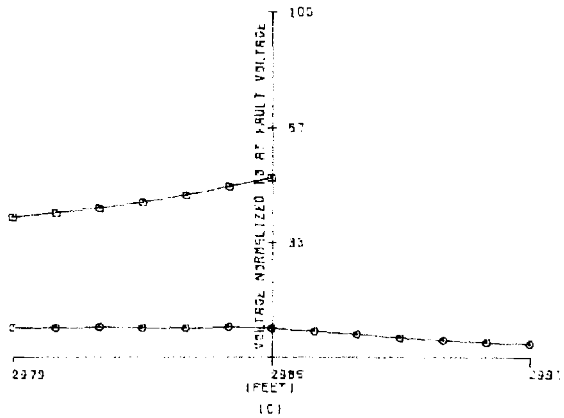


FIGURE B.103 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.8730 OHMS.
ZGC = 34.7395 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.104 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

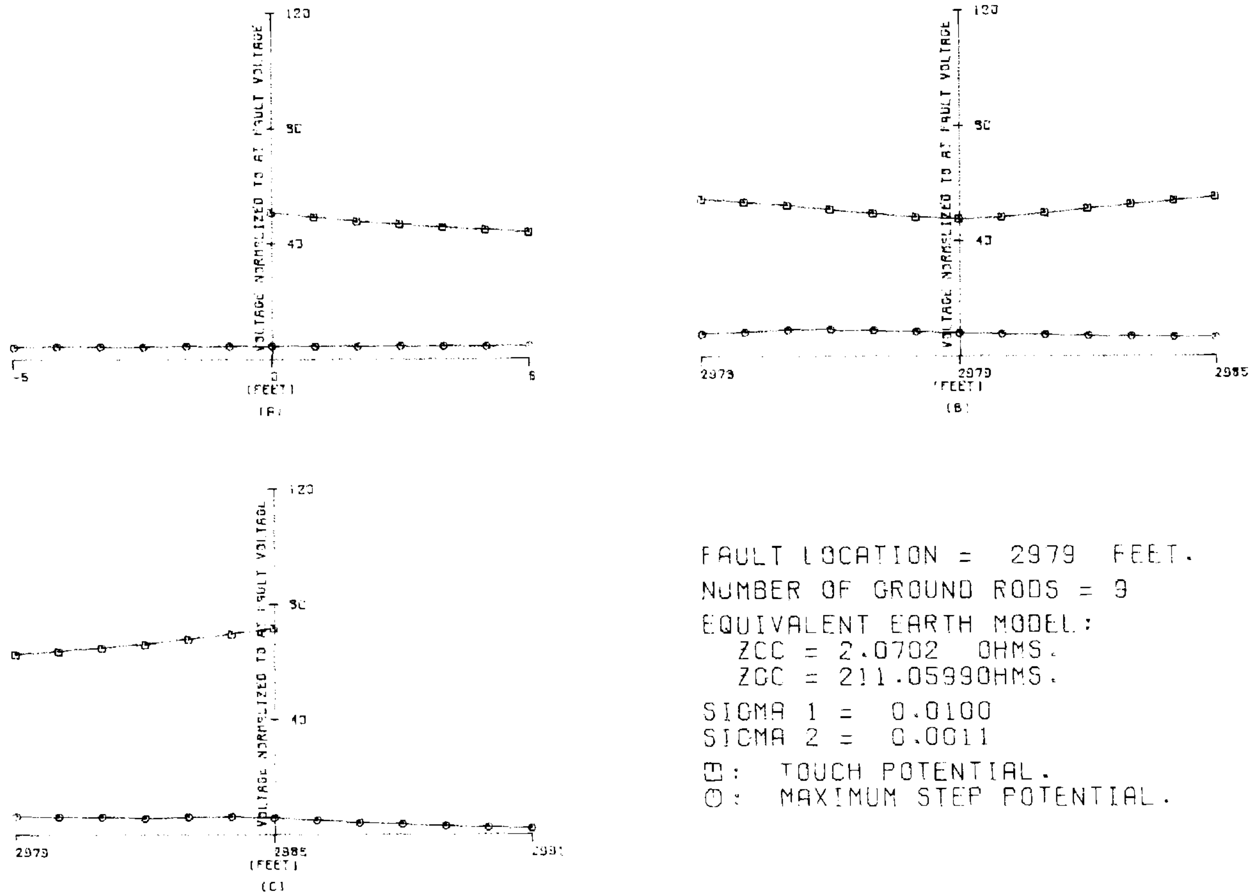
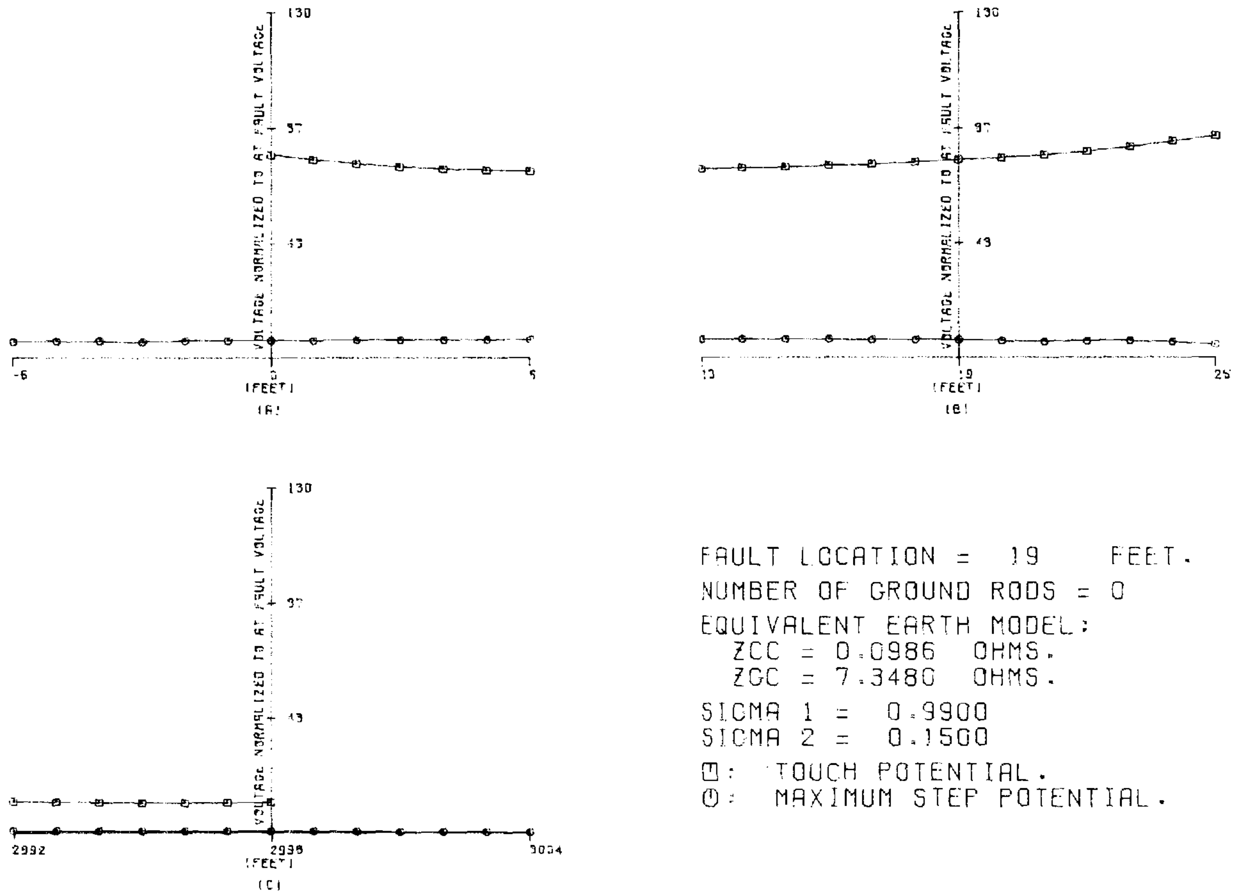
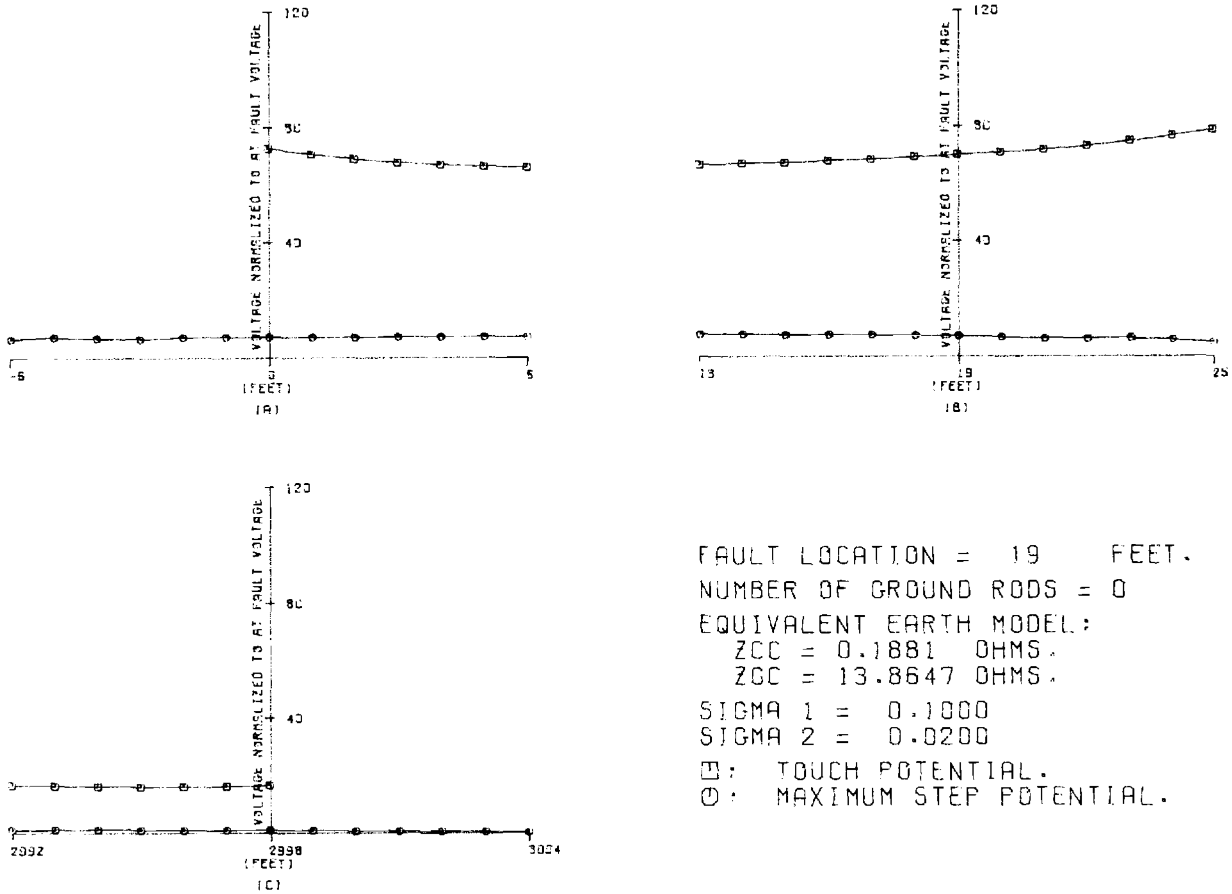


FIGURE B.105 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



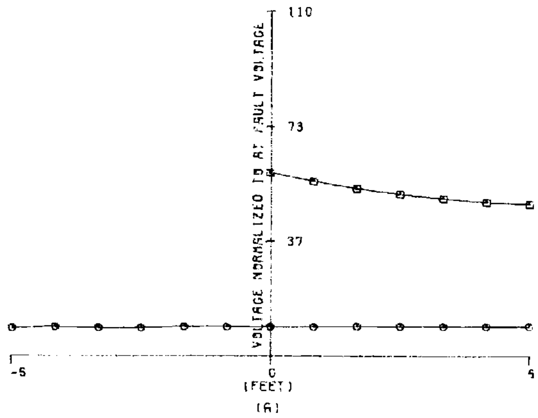
FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.0986 OHMS.
ZGC = 7.3480 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
⊖: MAXIMUM STEP POTENTIAL.

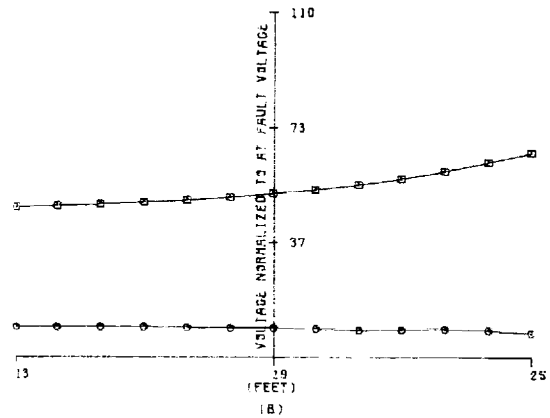
FIGURE B.106 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

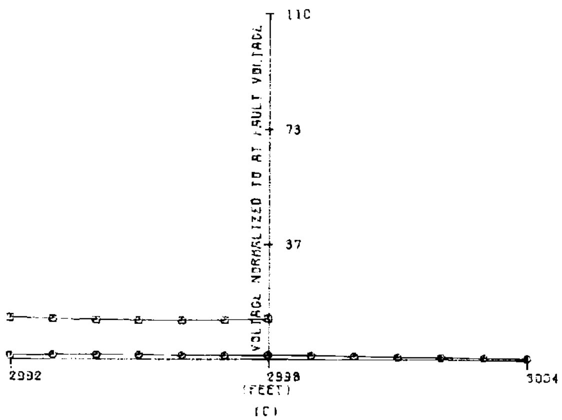


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1881 OHMS.
ZCC = 13.8647 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
▢: TOUCH POTENTIAL.
◯: MAXIMUM STEP POTENTIAL.

FIGURE B.107 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

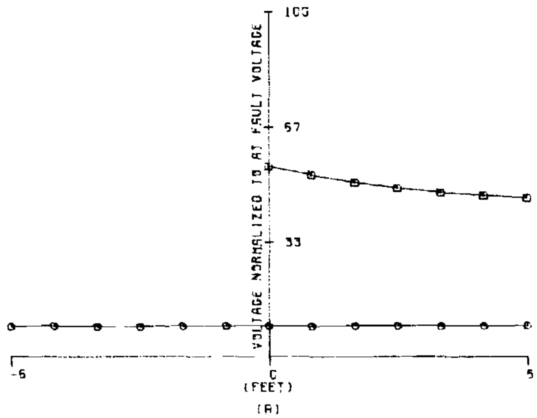


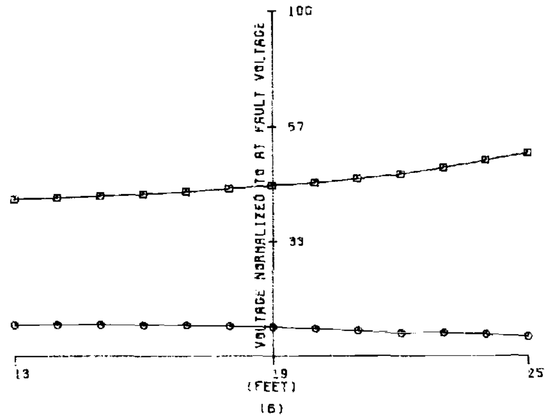


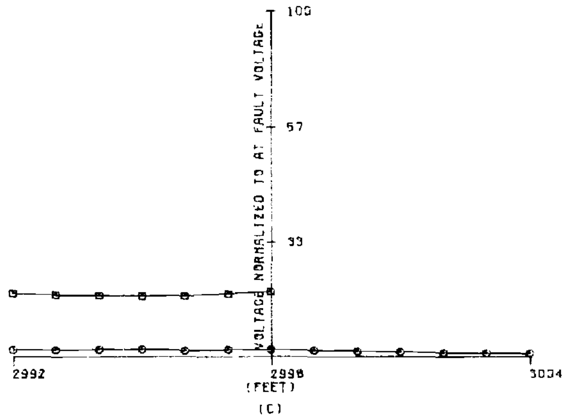


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1470 OHMS.
ZGC = 5.7225 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.108 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

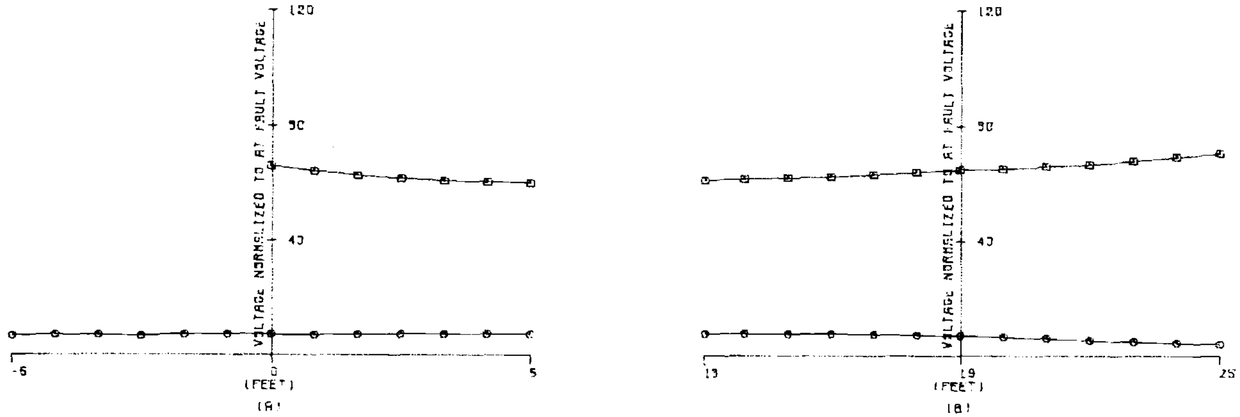


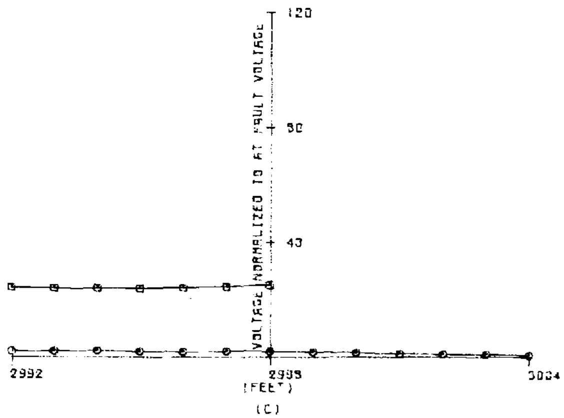




FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.3474 OHMS.
ZGC = 13.7223 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
T: TOUCH POTENTIAL.
O: MAXIMUM STEP POTENTIAL.

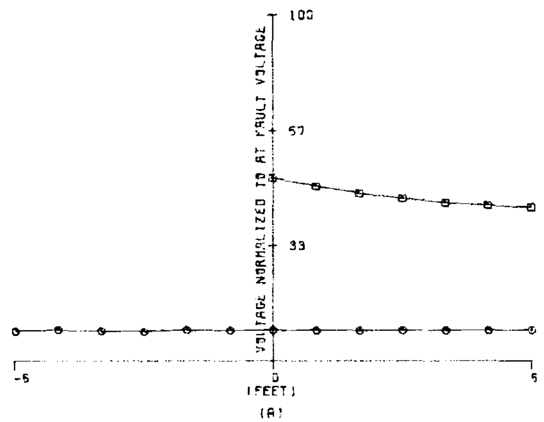
FIGURE B.109 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

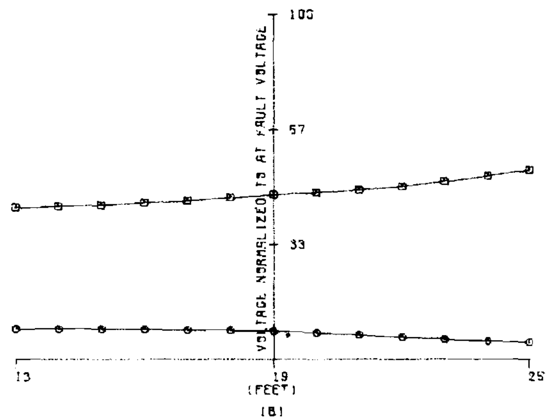


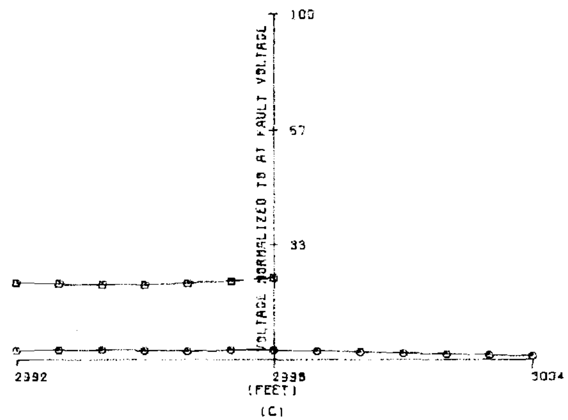


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.4394 OHMS.
ZGC = 30.2396 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.110 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5296 OHMS.
ZGC = 21.7069 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.111 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

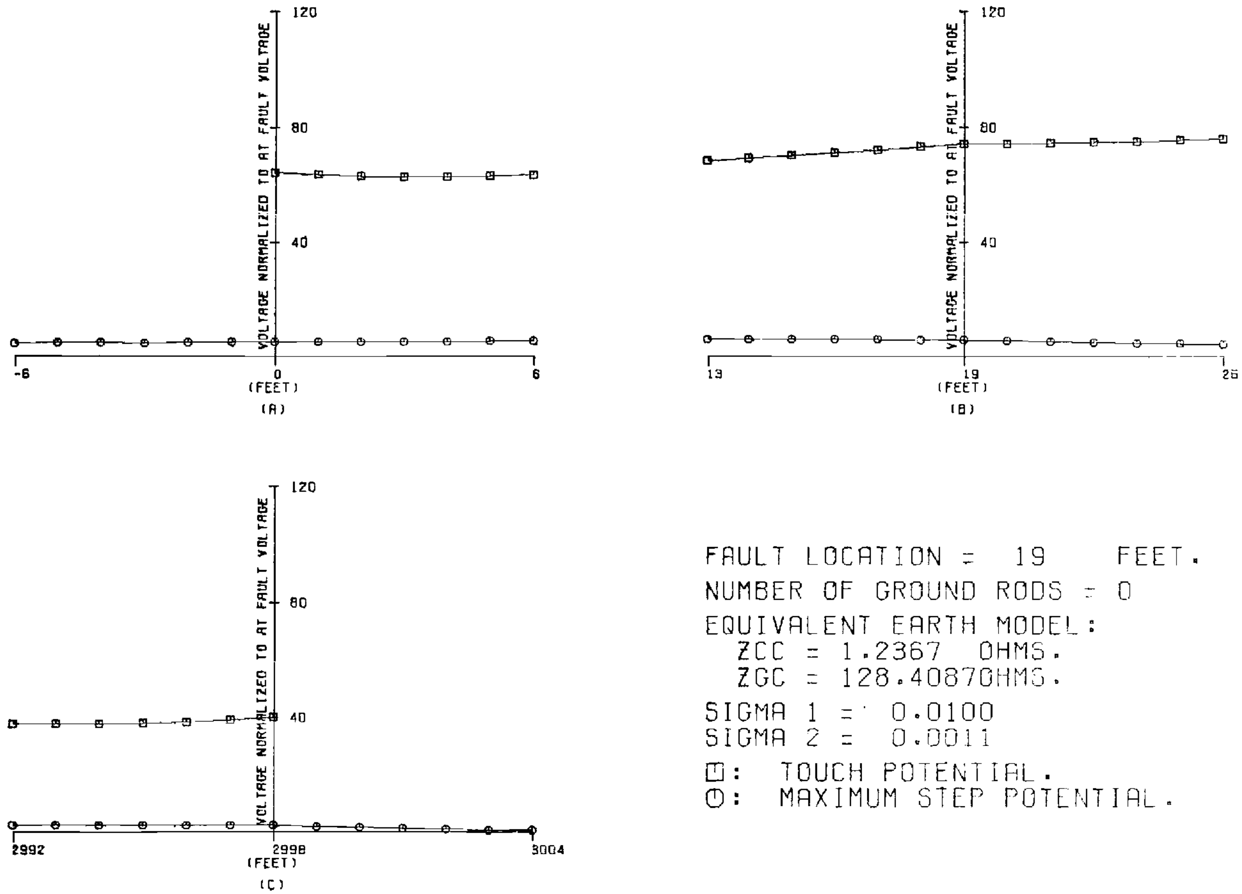


FIGURE B.112 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

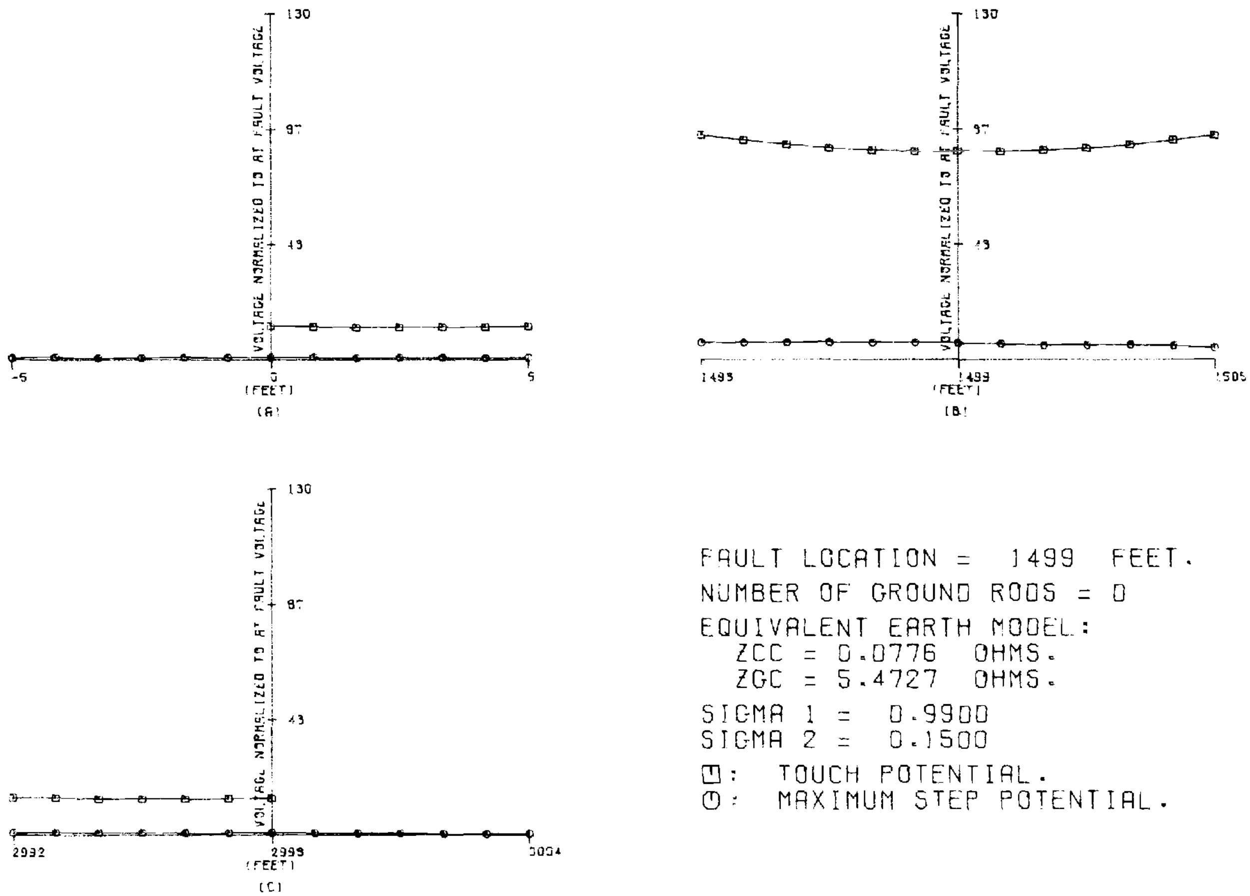
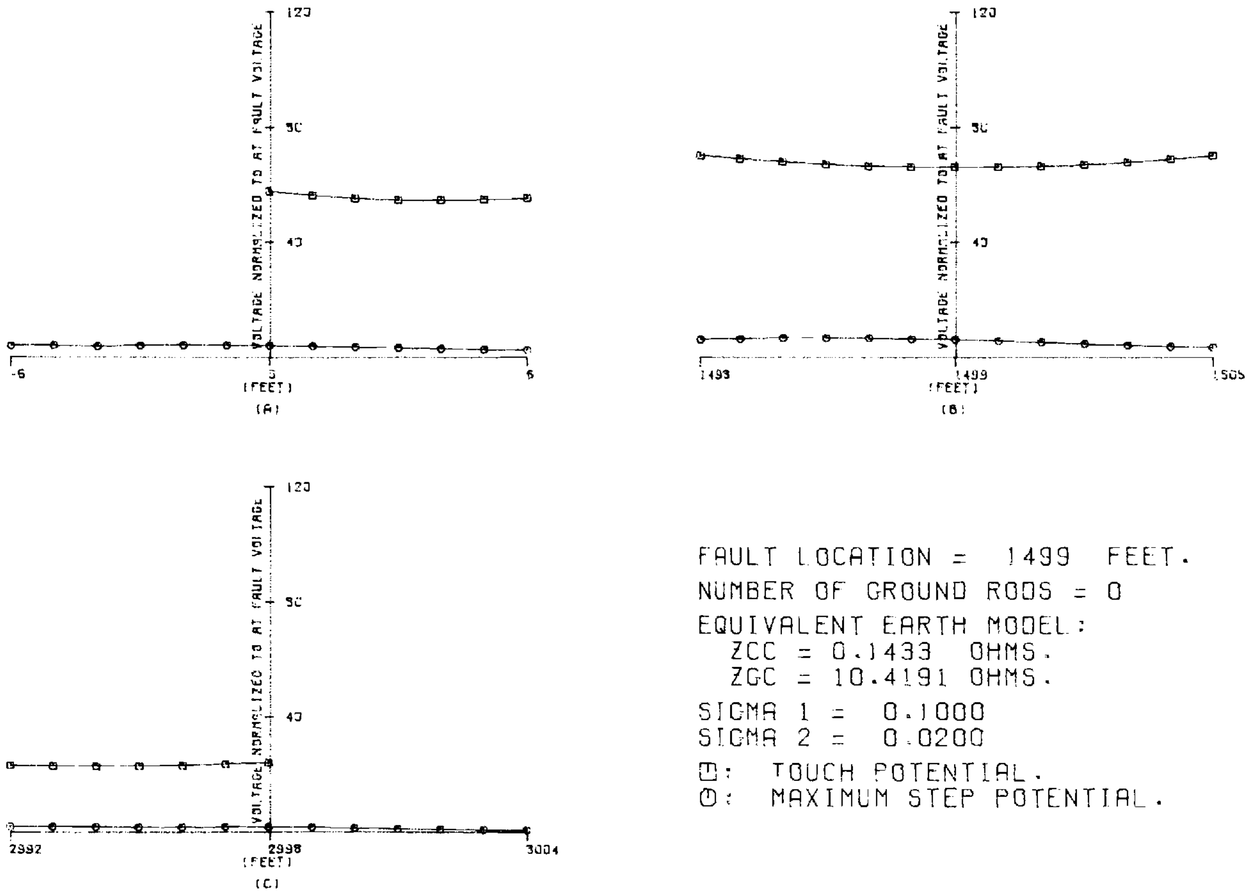
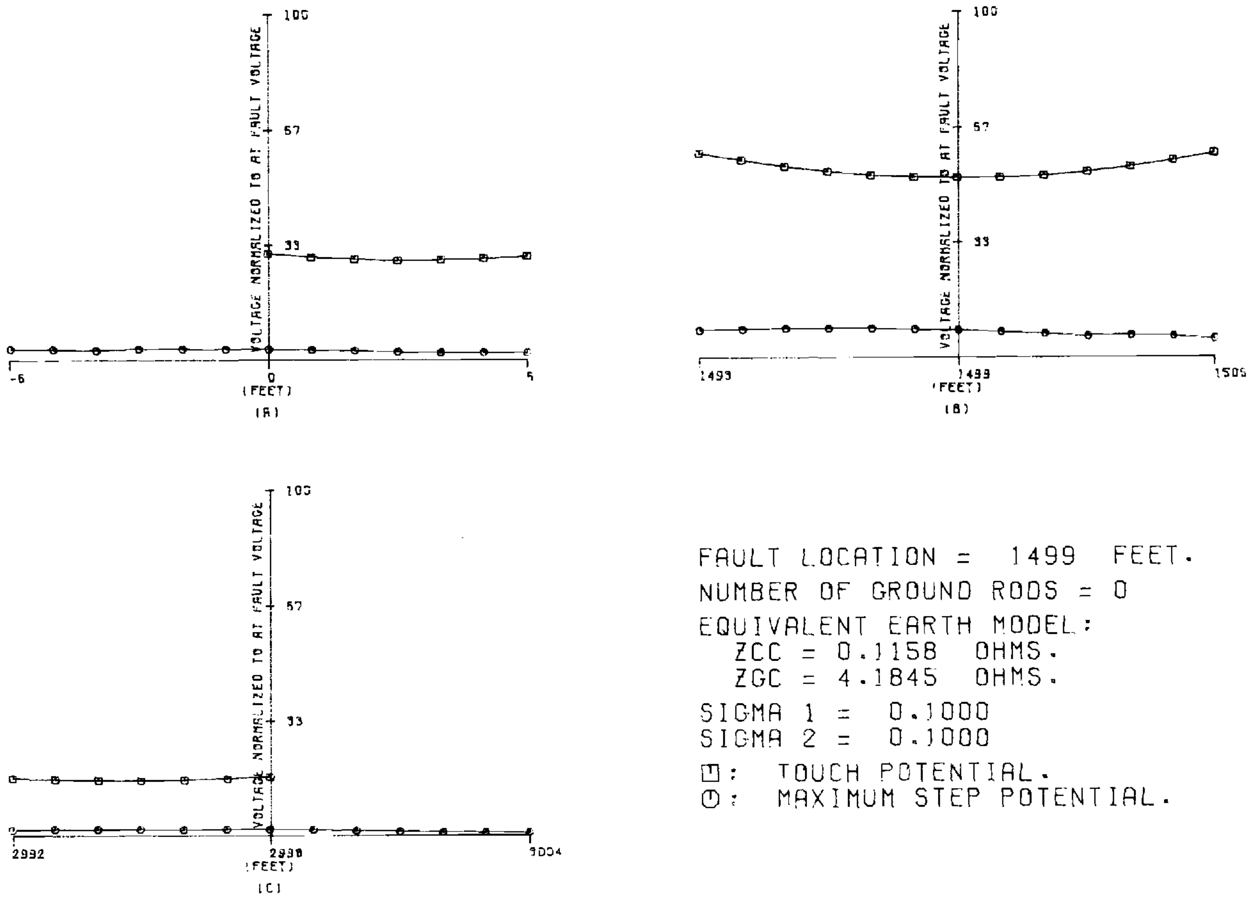


FIGURE B.113 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1433 OHMS.
ZGC = 10.4191 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.114 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1158 OHMS.
ZGC = 4.1845 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.115 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

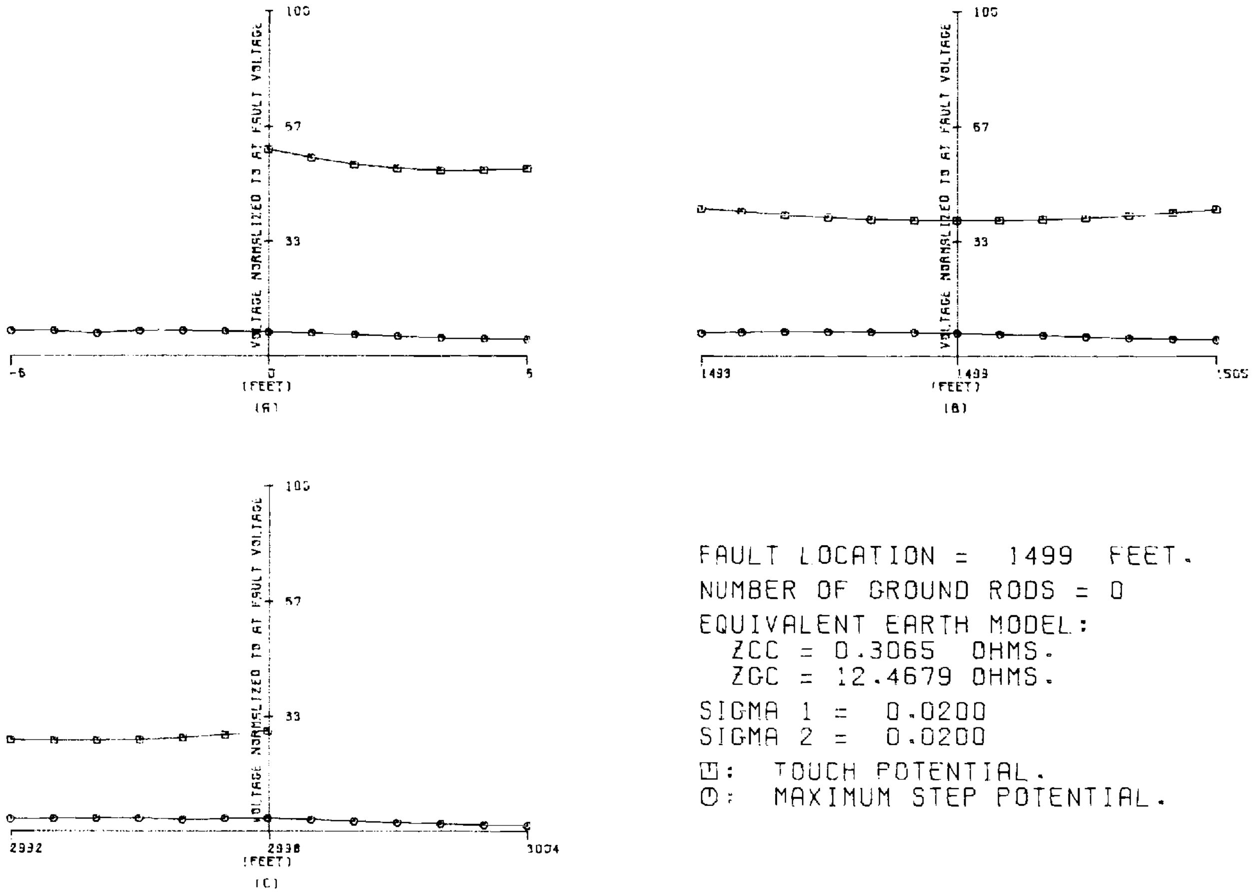
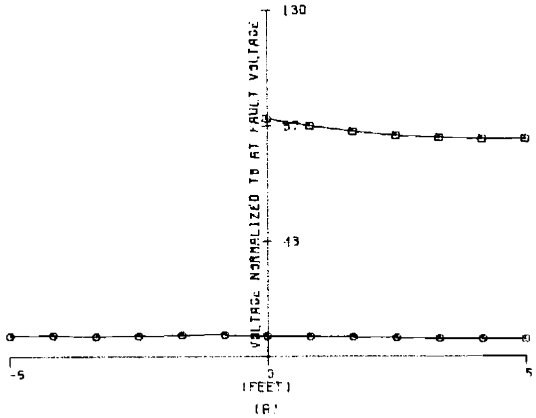
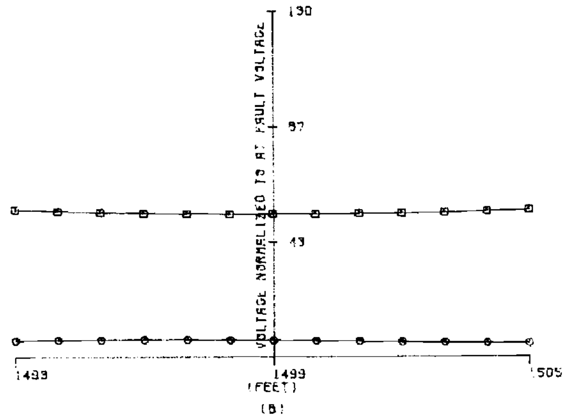
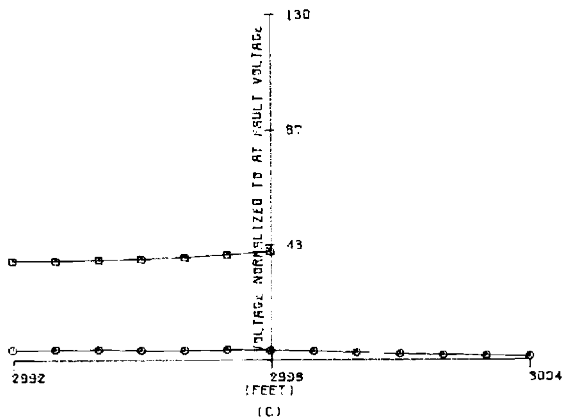


FIGURE B.116 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

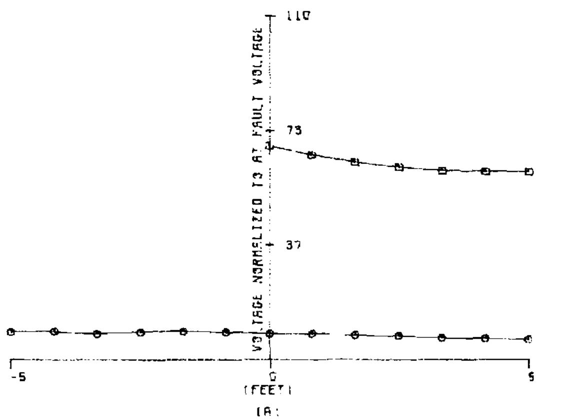


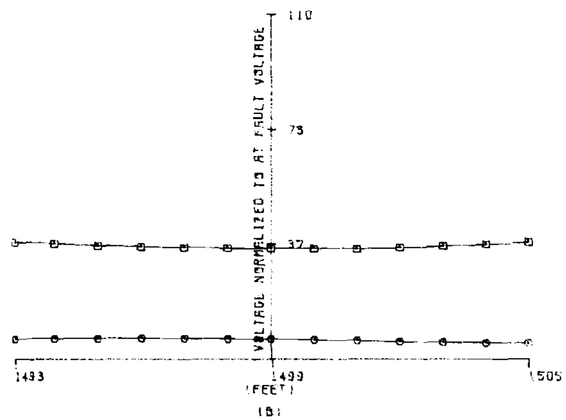


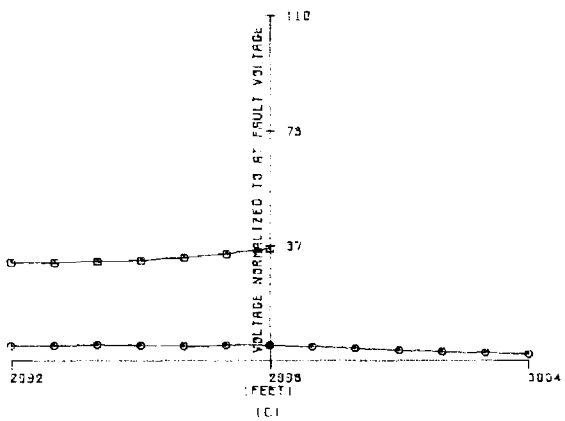


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.4447 OHMS.
ZGC = 30.9313 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.117 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

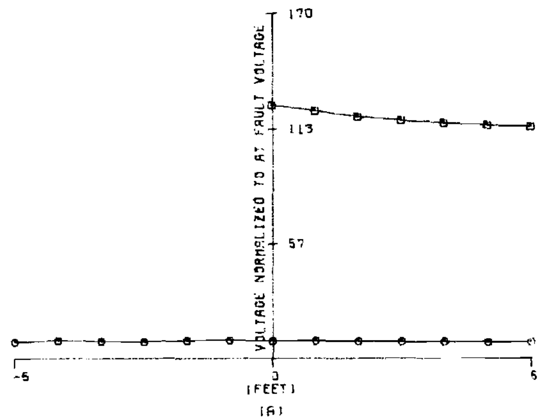


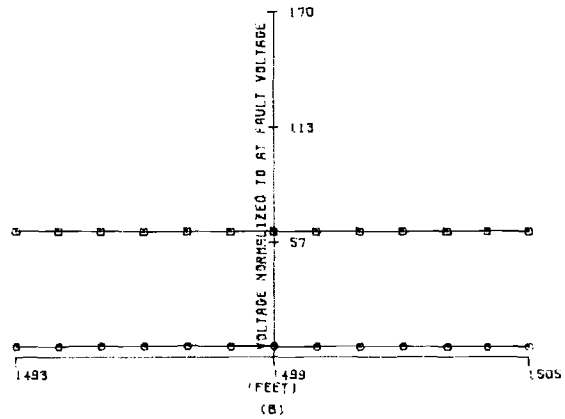


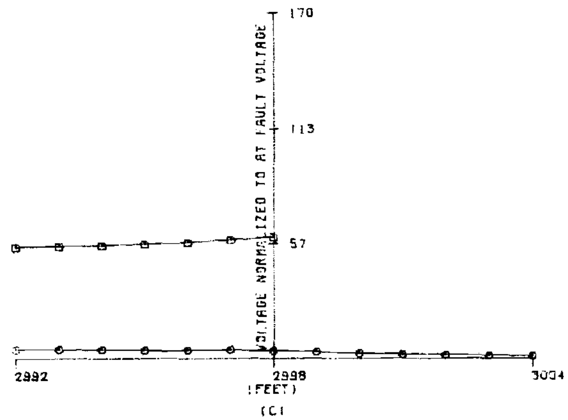


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5585 OHMS.
ZGC = 23.0690 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.118 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

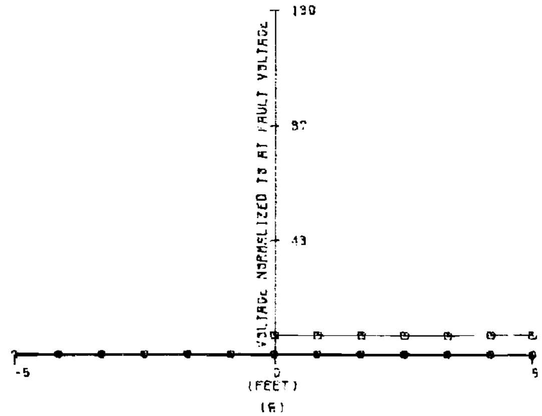


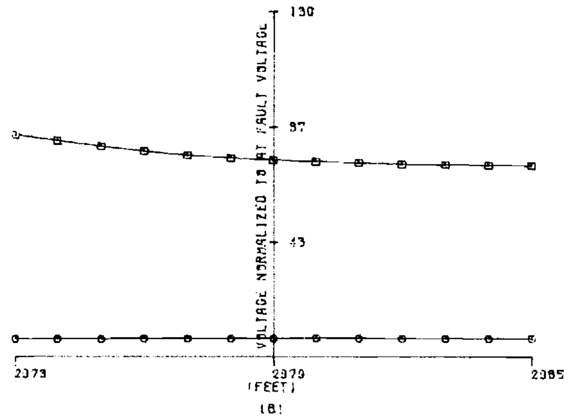


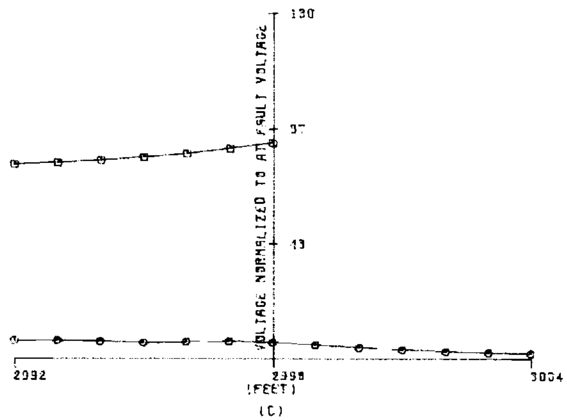


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 1.2346 OHMS.
ZGC = 137.1345OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.119 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

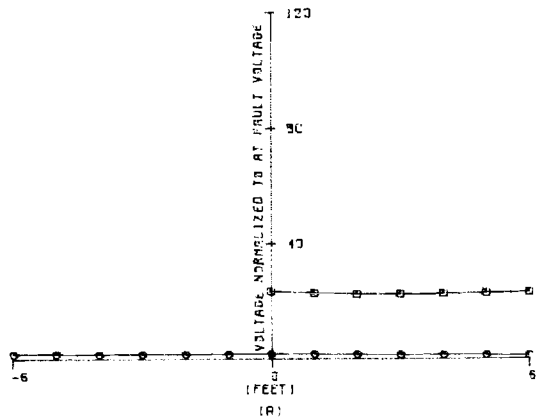


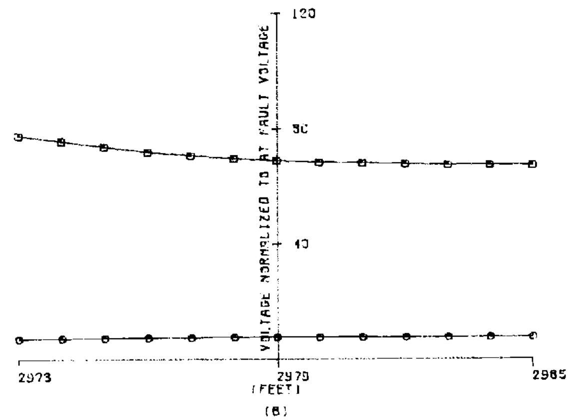


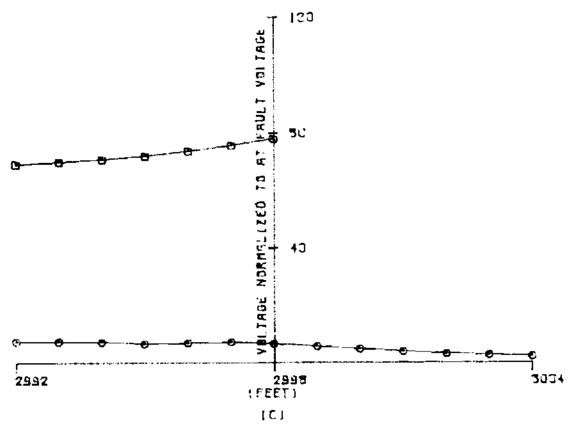


FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1121 OHMS.
ZGC = 8.2755 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.120 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.2657 OHMS.
ZGC = 19.4235 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.121 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

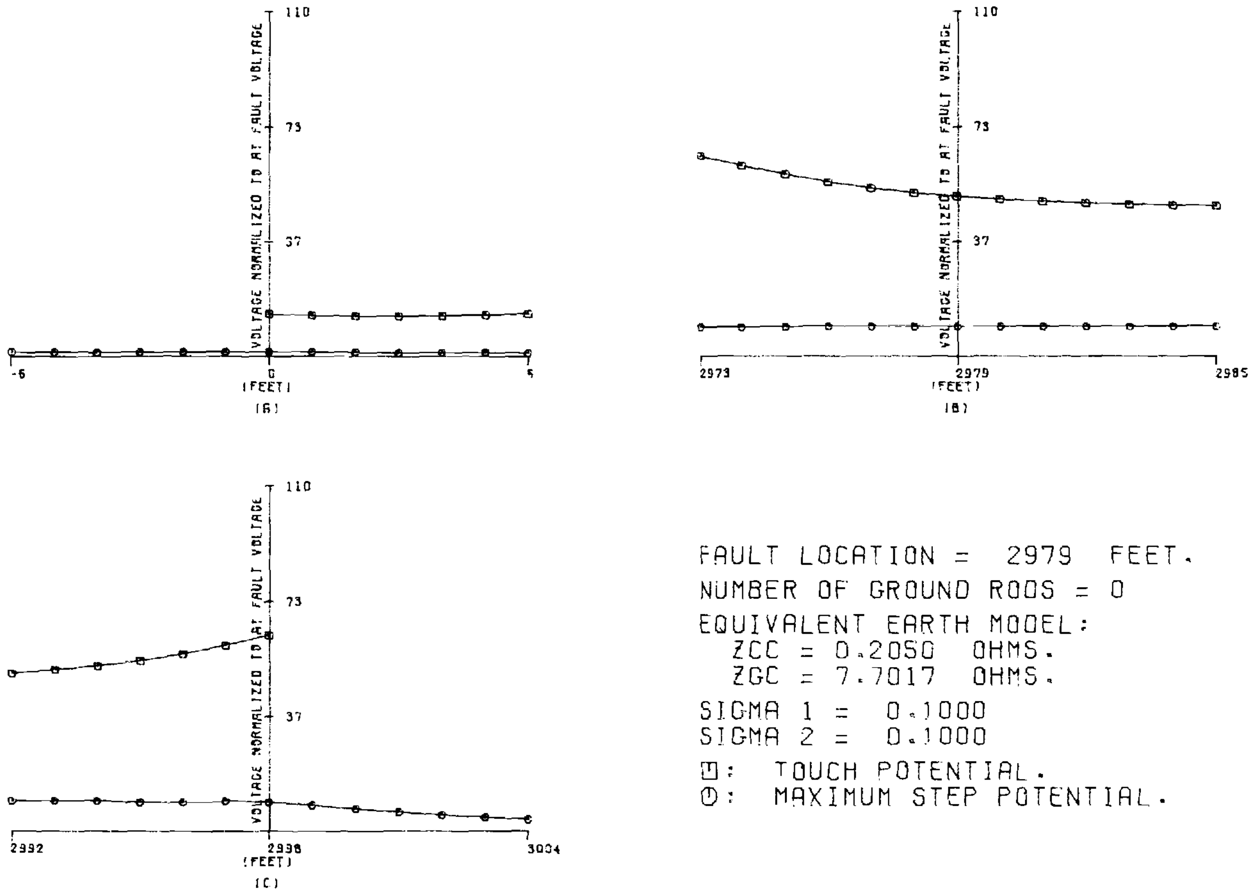


FIGURE B.122 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

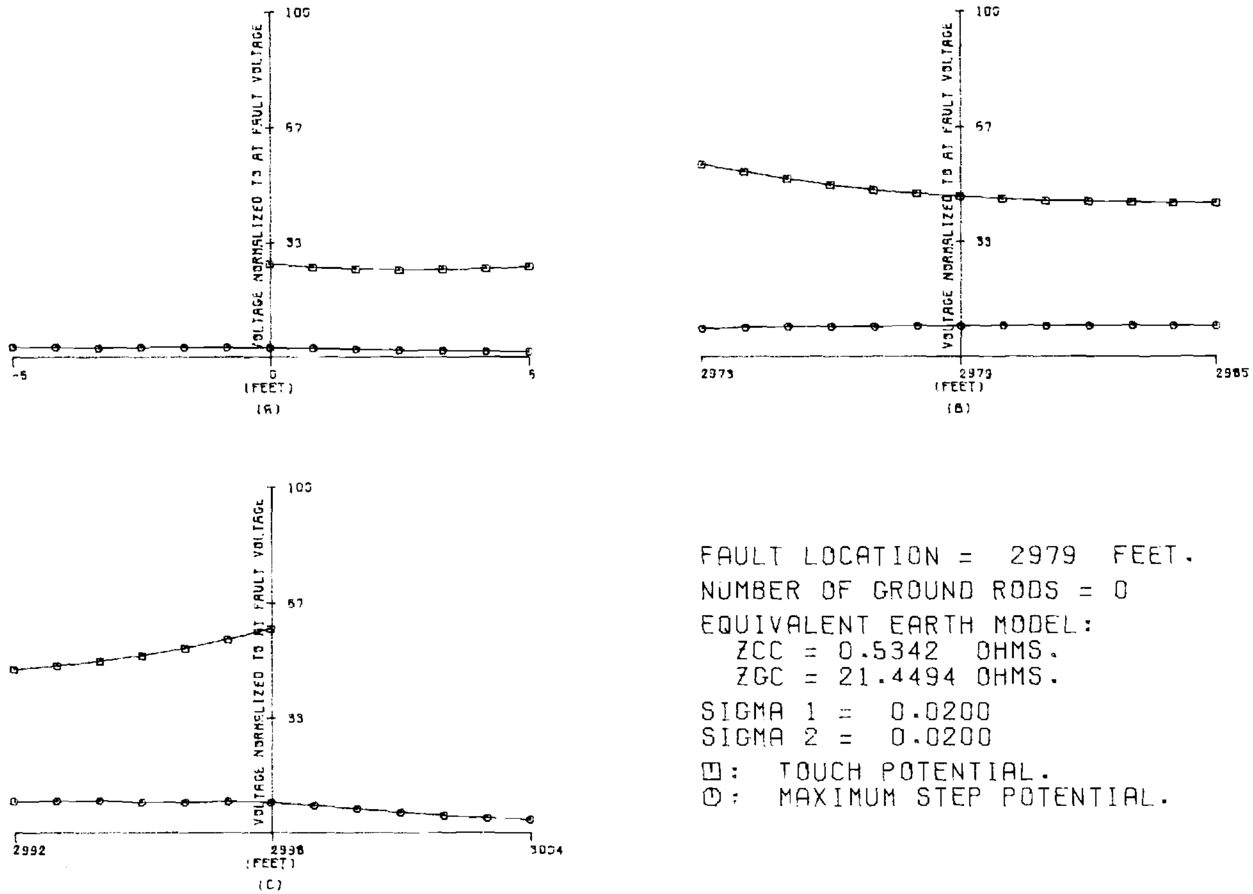
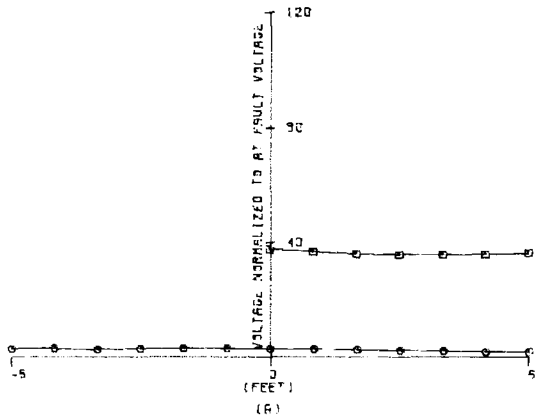
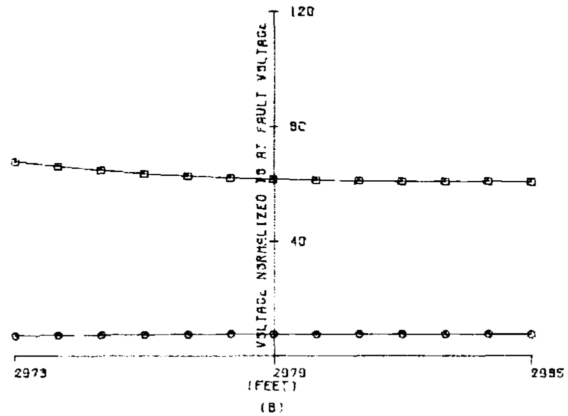
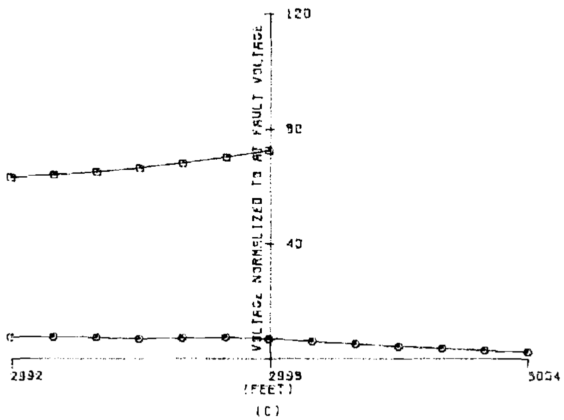


FIGURE B.123 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

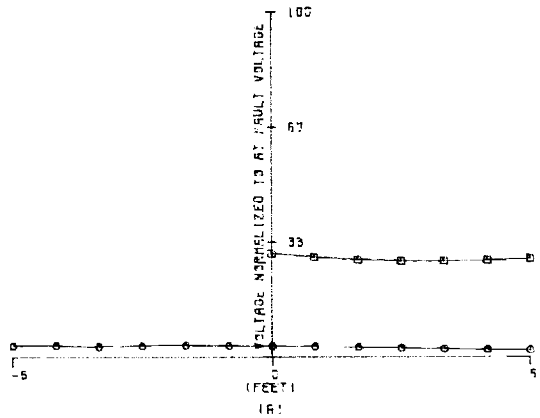


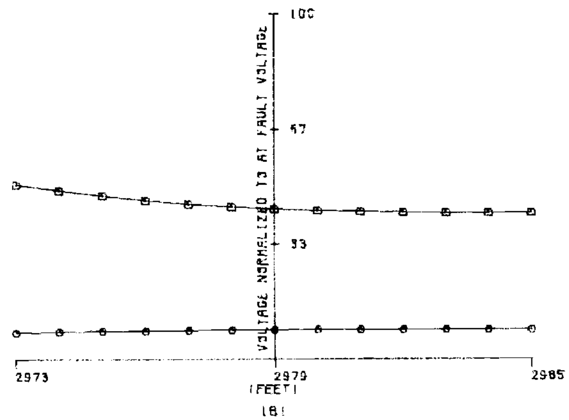


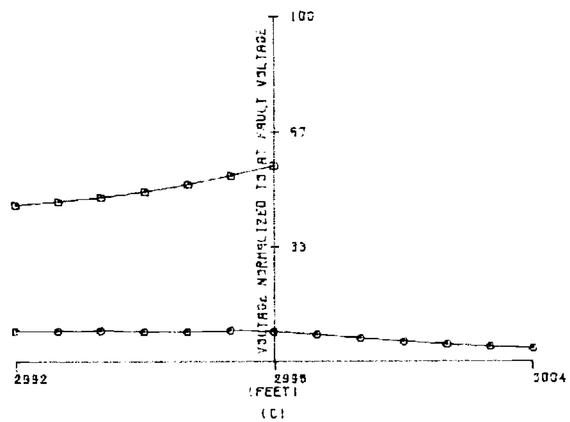


FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.7904 OHMS.
ZGC = 53.2050 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.124 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

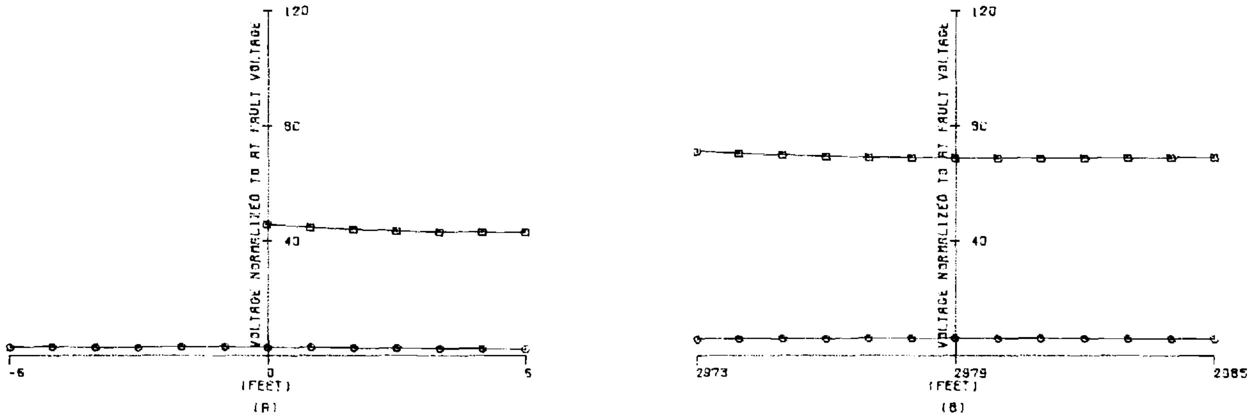


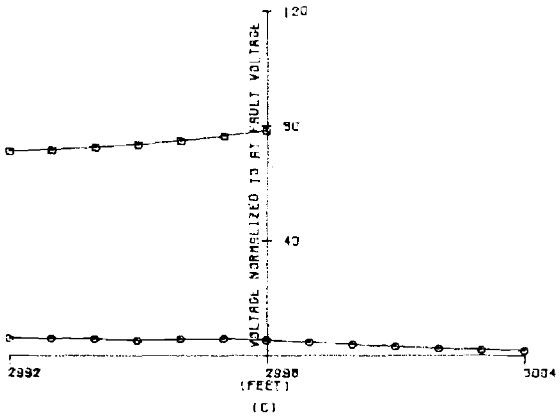




FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.9698 OHMS.
ZGC = 39.0901 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

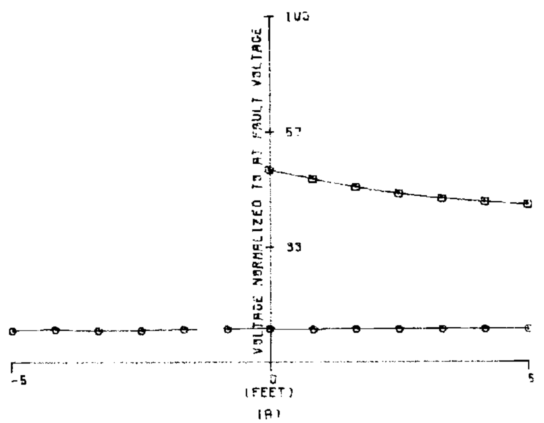
FIGURE B.125 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

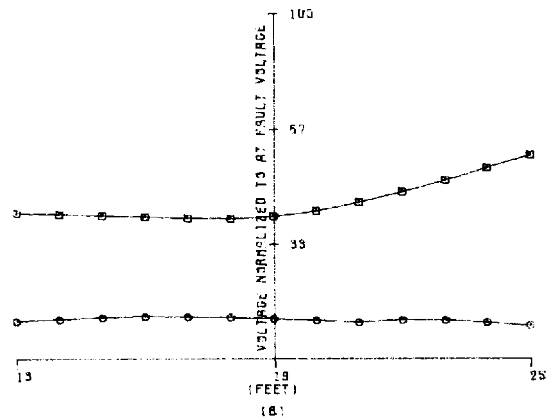


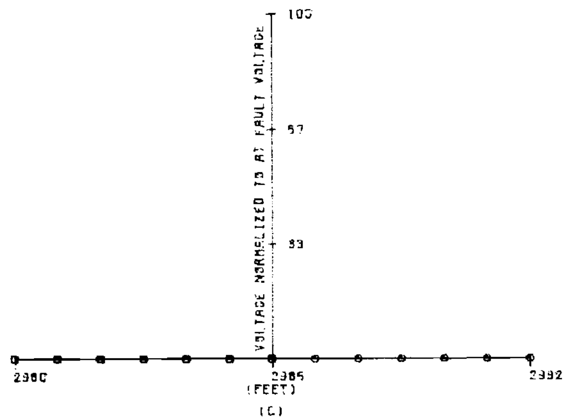


FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 2.3254 OHMS.
ZGC = 245.3638OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.126 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

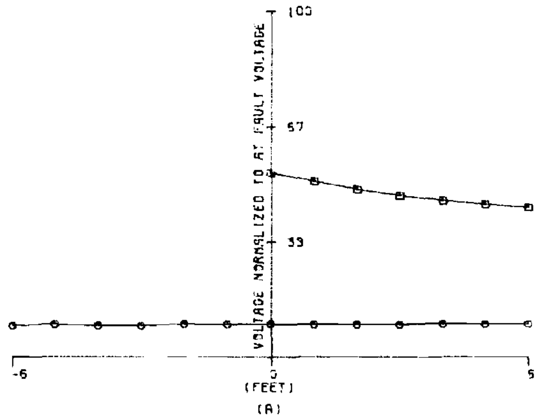


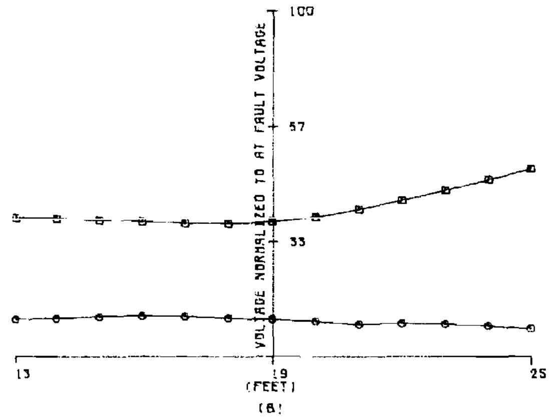


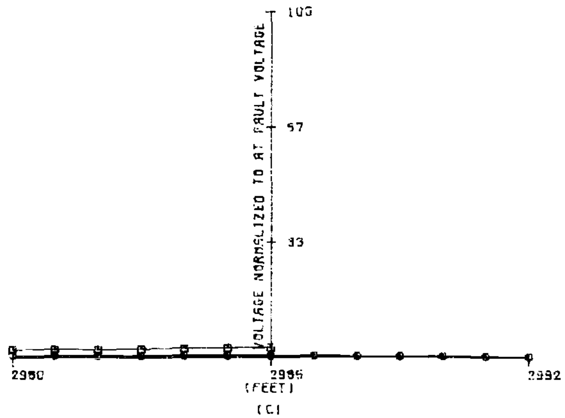


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.0657 OHMS.
ZGC = 4.1934 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.127 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

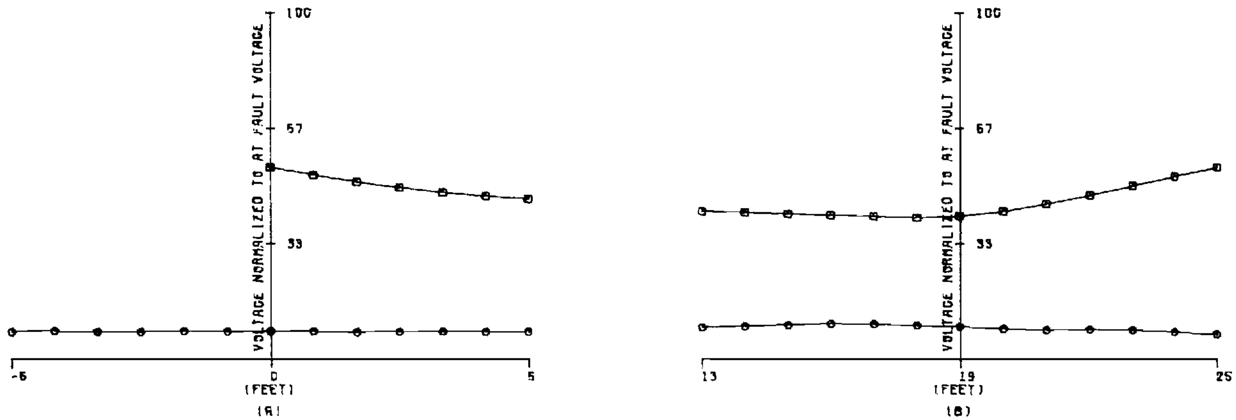


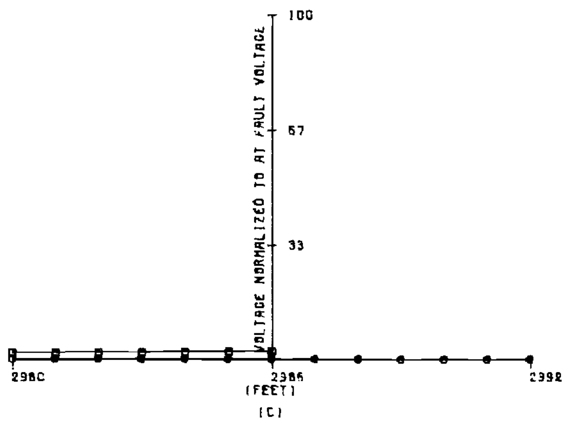




FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1431 OHMS.
ZGC = 9.3133 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
☐: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

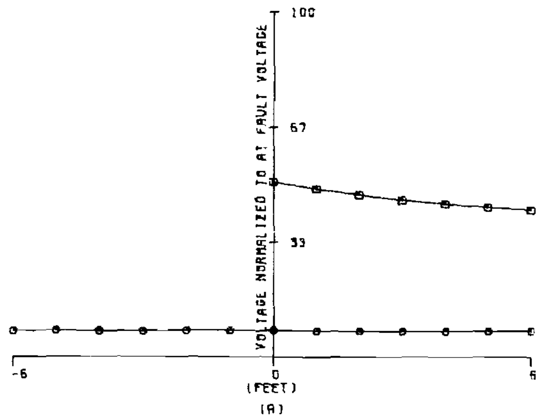
FIGURE B.128 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

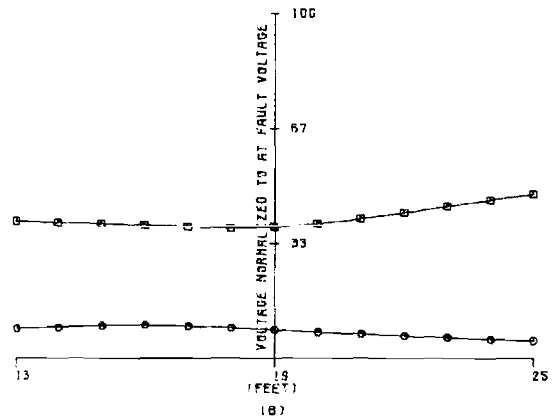


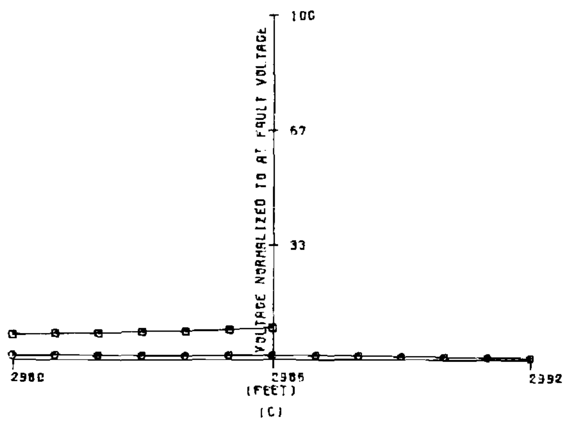


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1244 OHMS.
ZGC = 4.5636 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.129 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.2891 OHMS.
ZGC = 11.5559 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.130 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

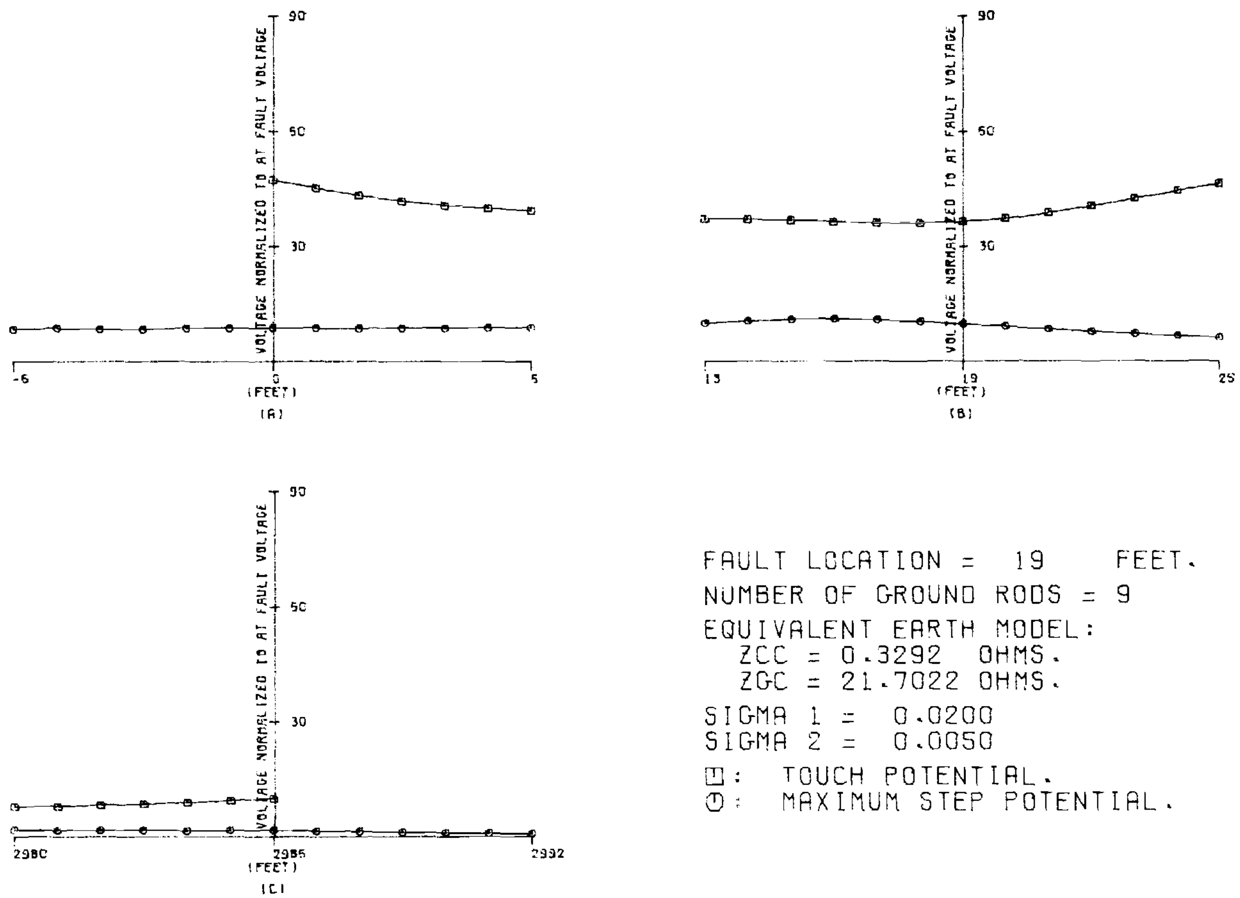
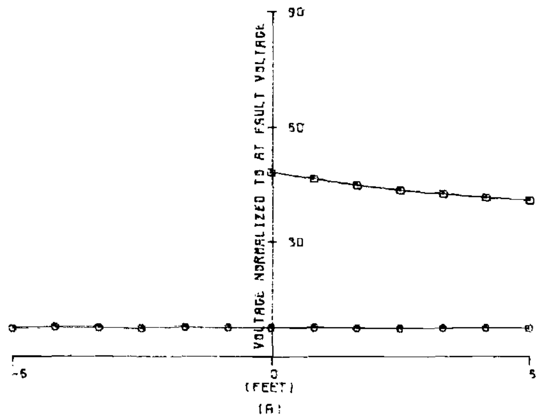
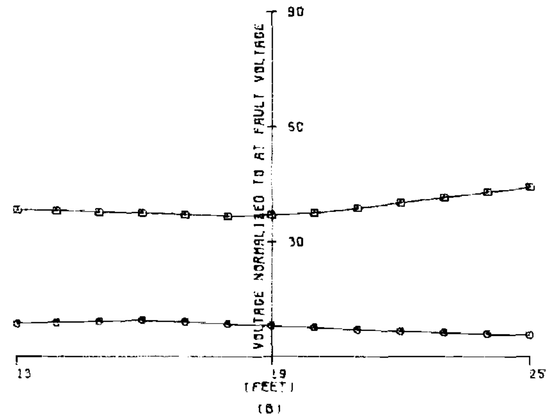
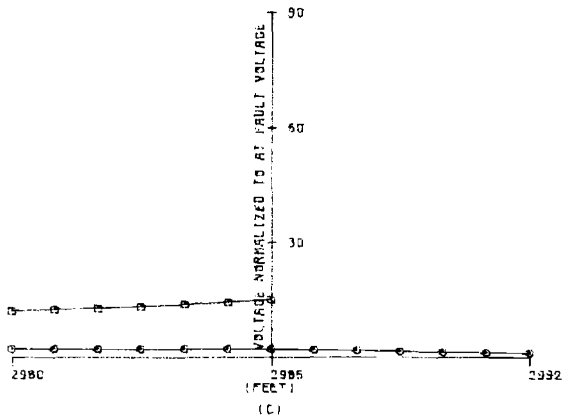


FIGURE B.131 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.4432 OHMS.
ZGC = 18.7547 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.132 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

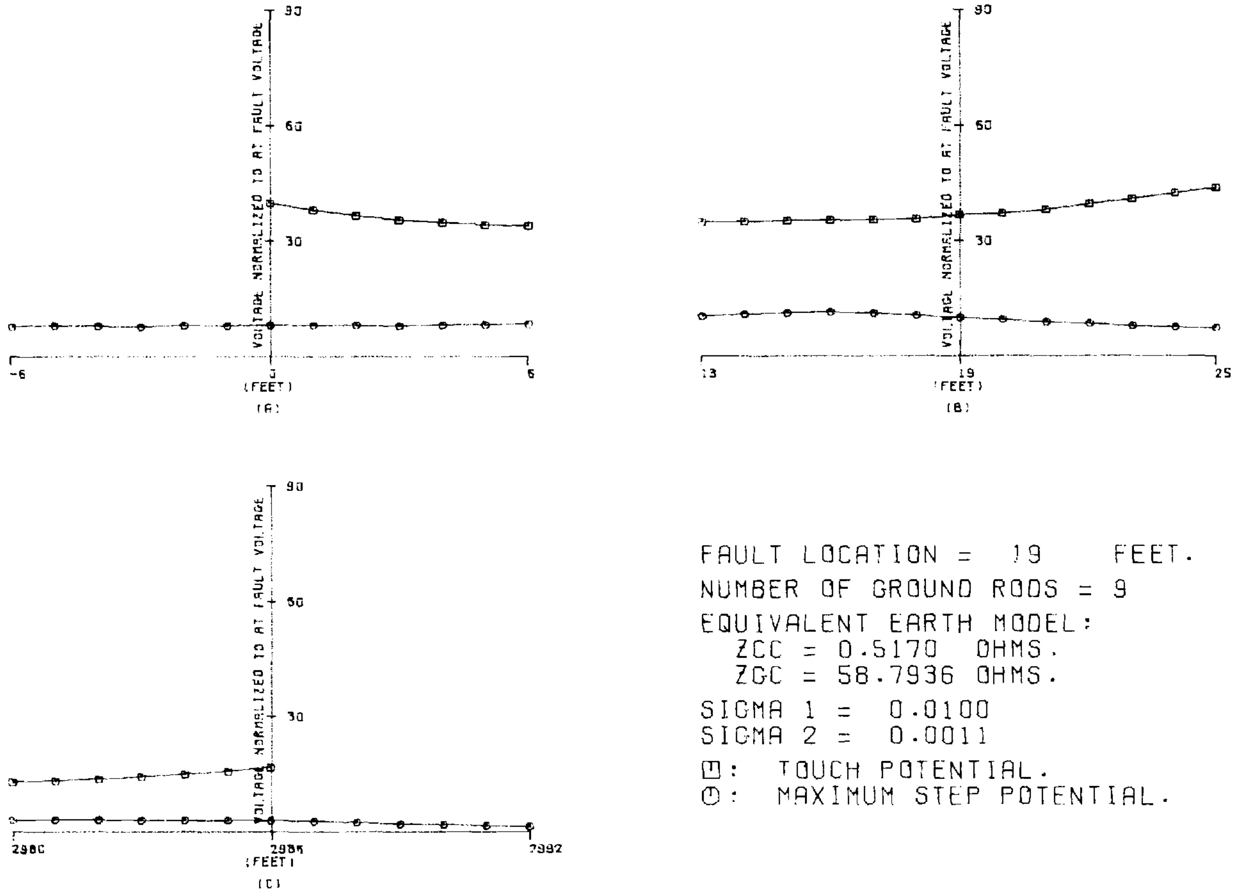
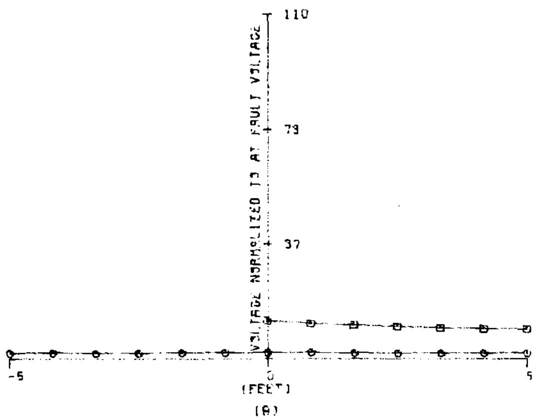
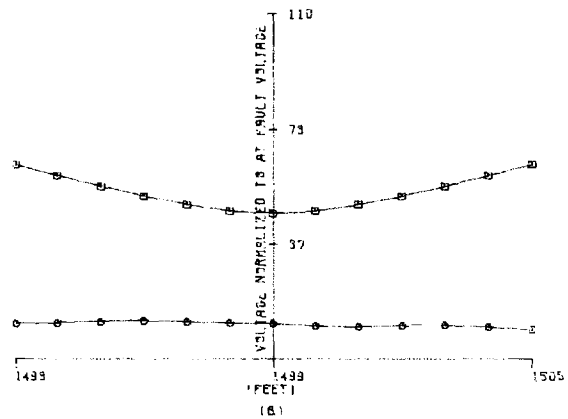
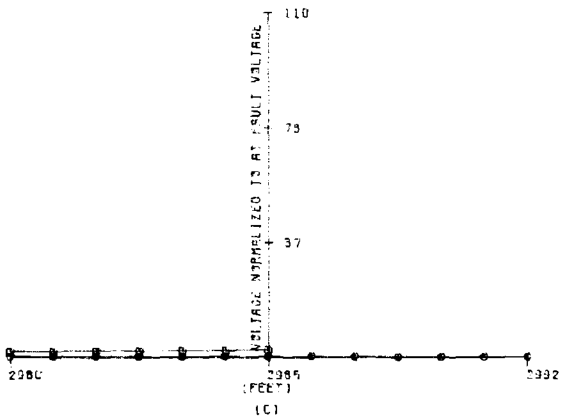


FIGURE B.133 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.0572 OHMS.
ZGC = 3.7314 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.134 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

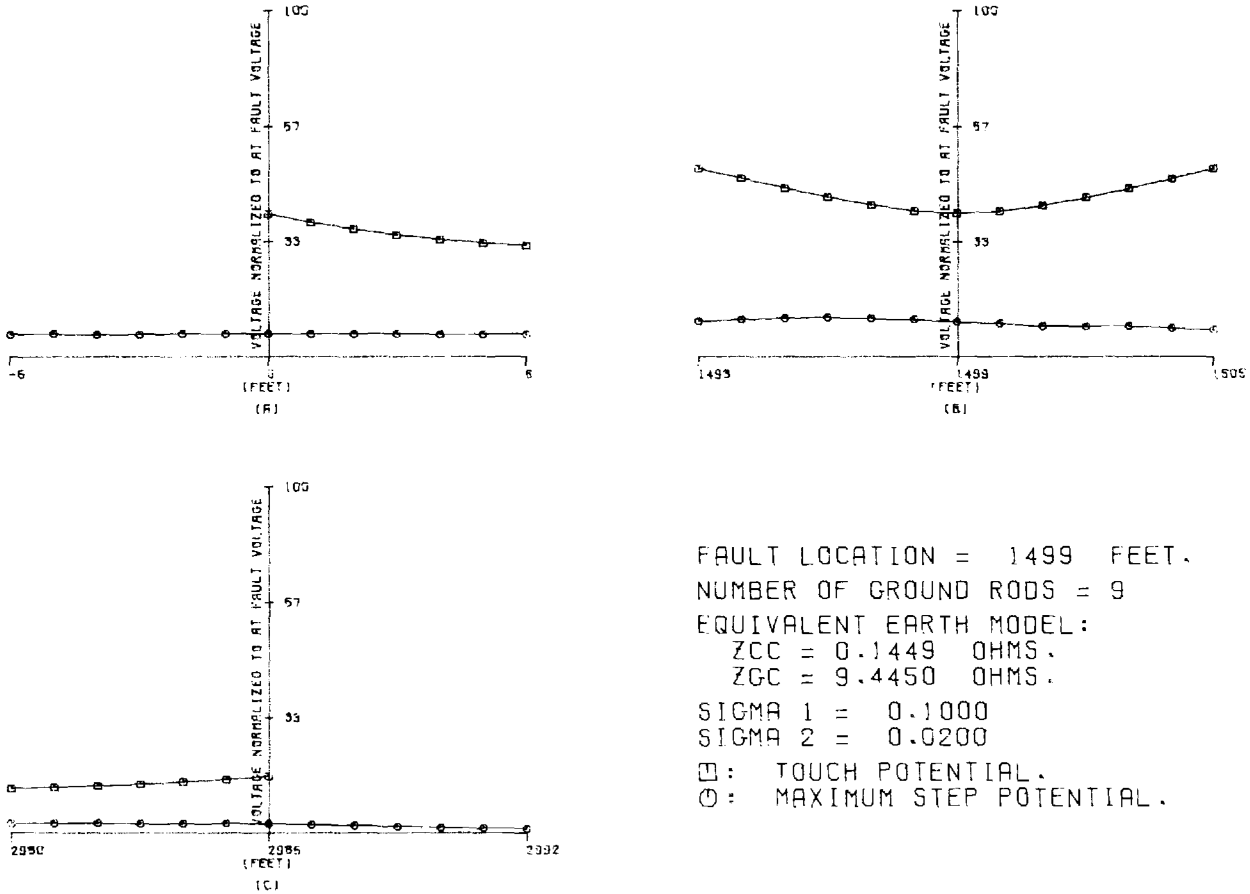


FIGURE B.135 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

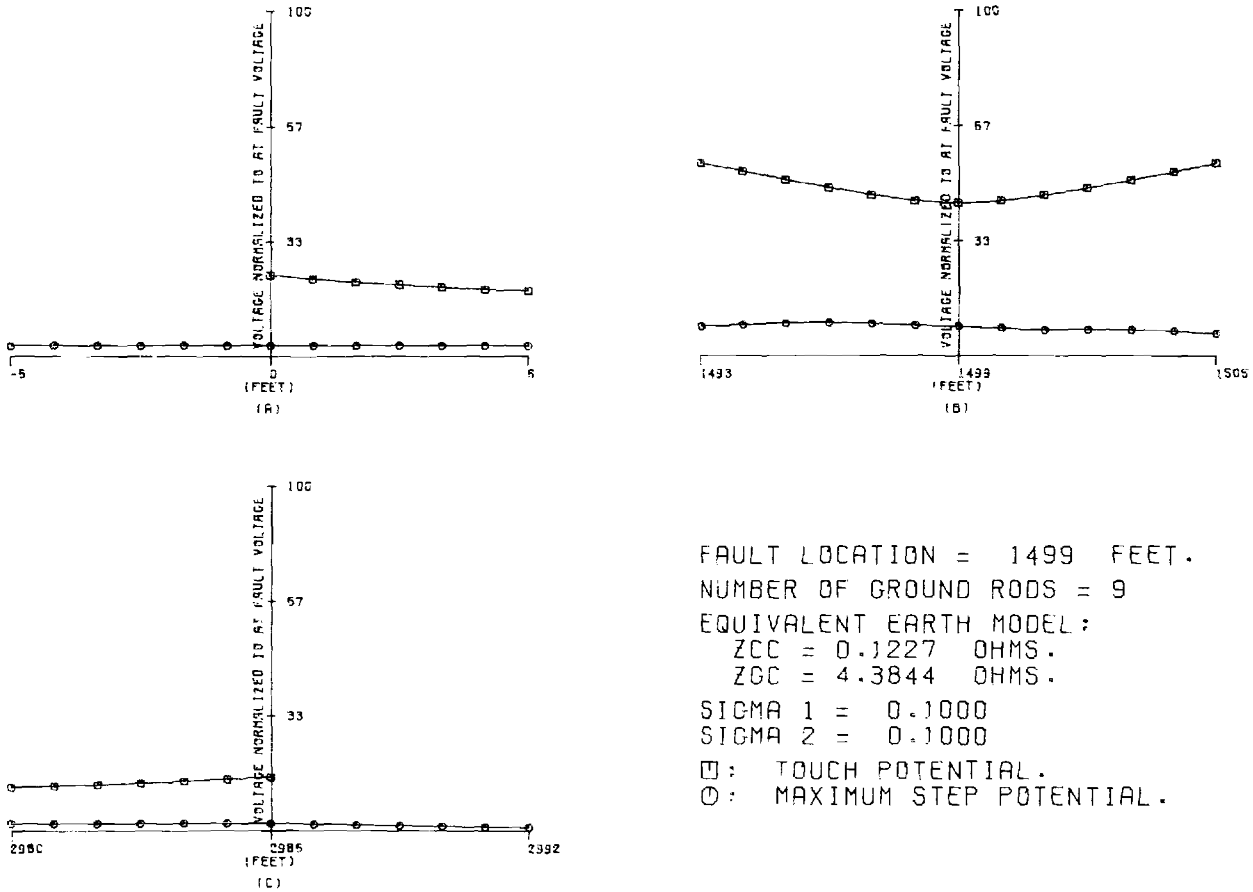


FIGURE B.136 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

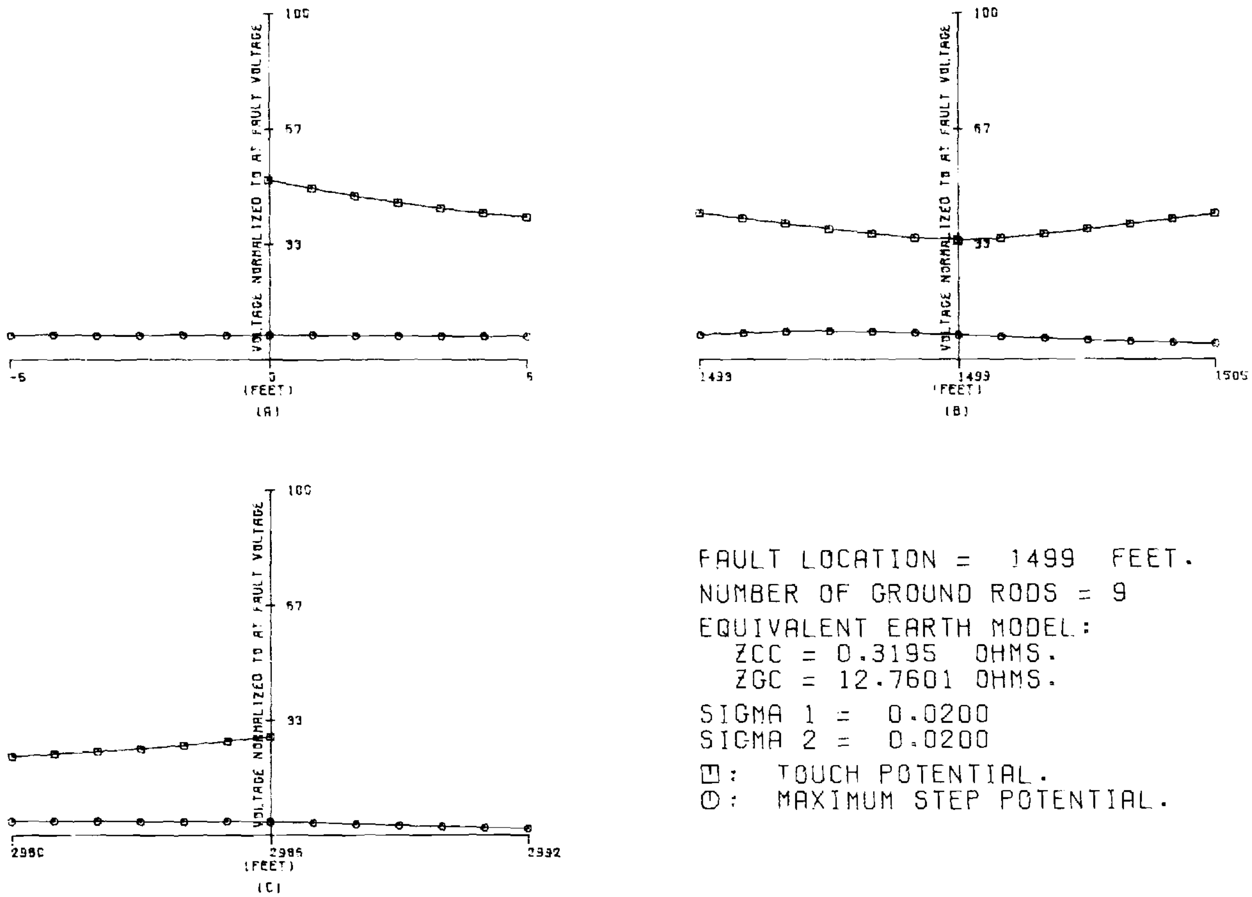


FIGURE B.137 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

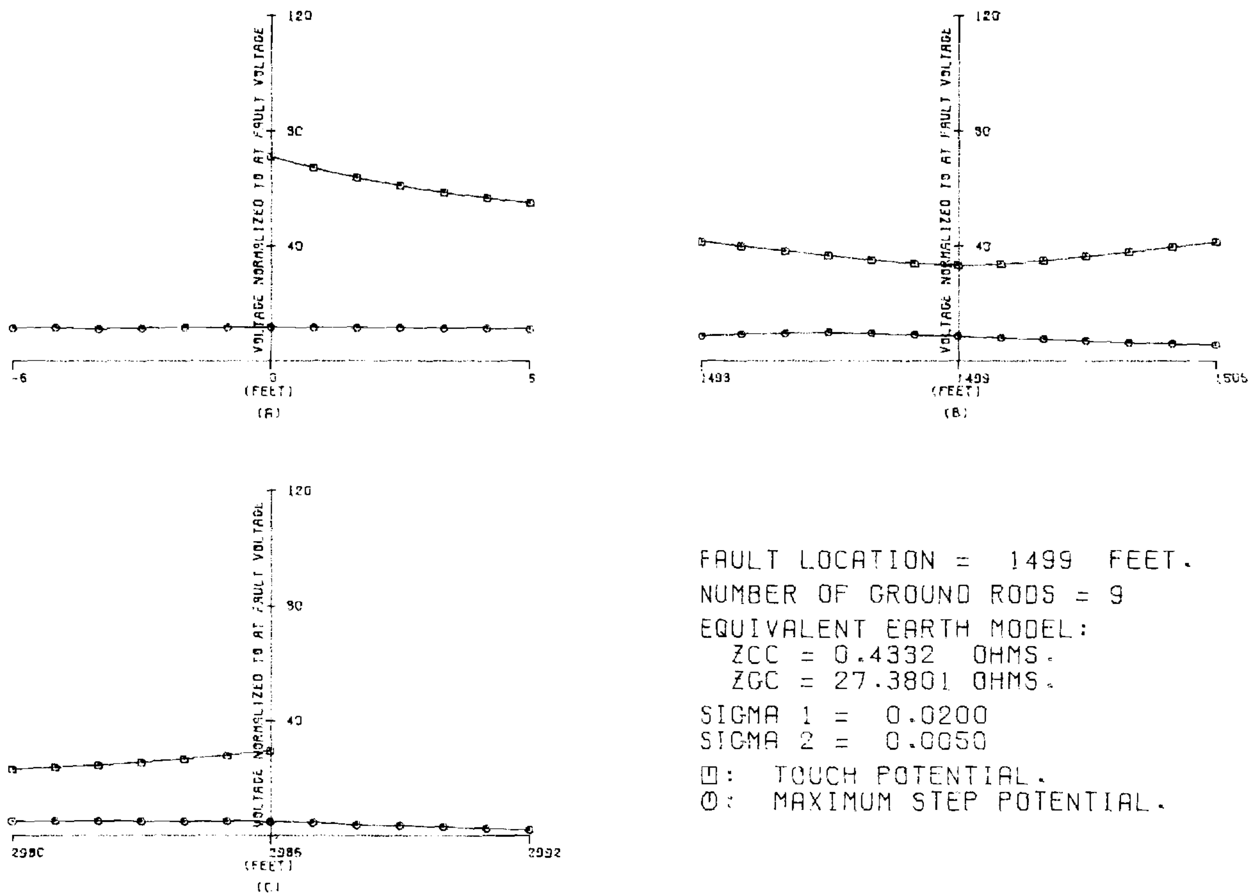


FIGURE B.138 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

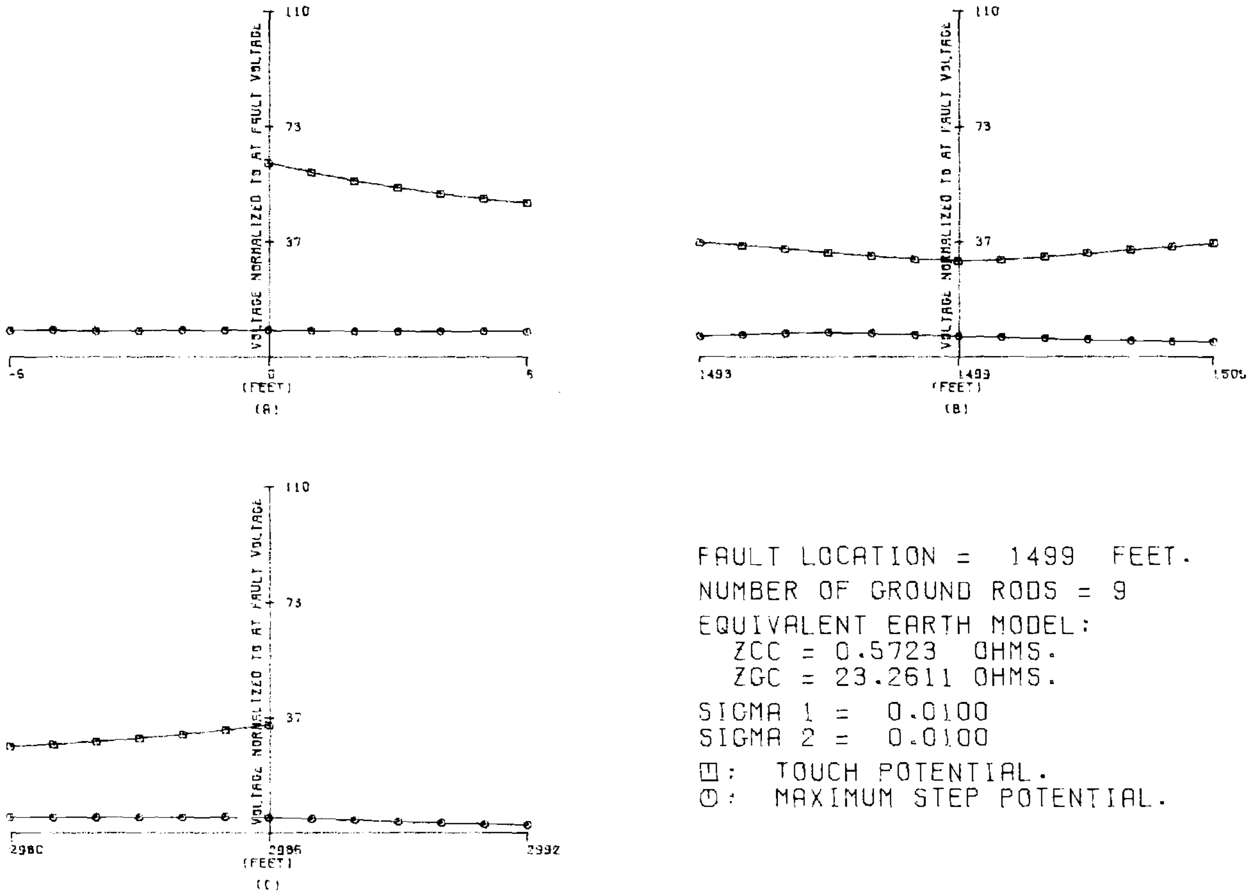


FIGURE B.139 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

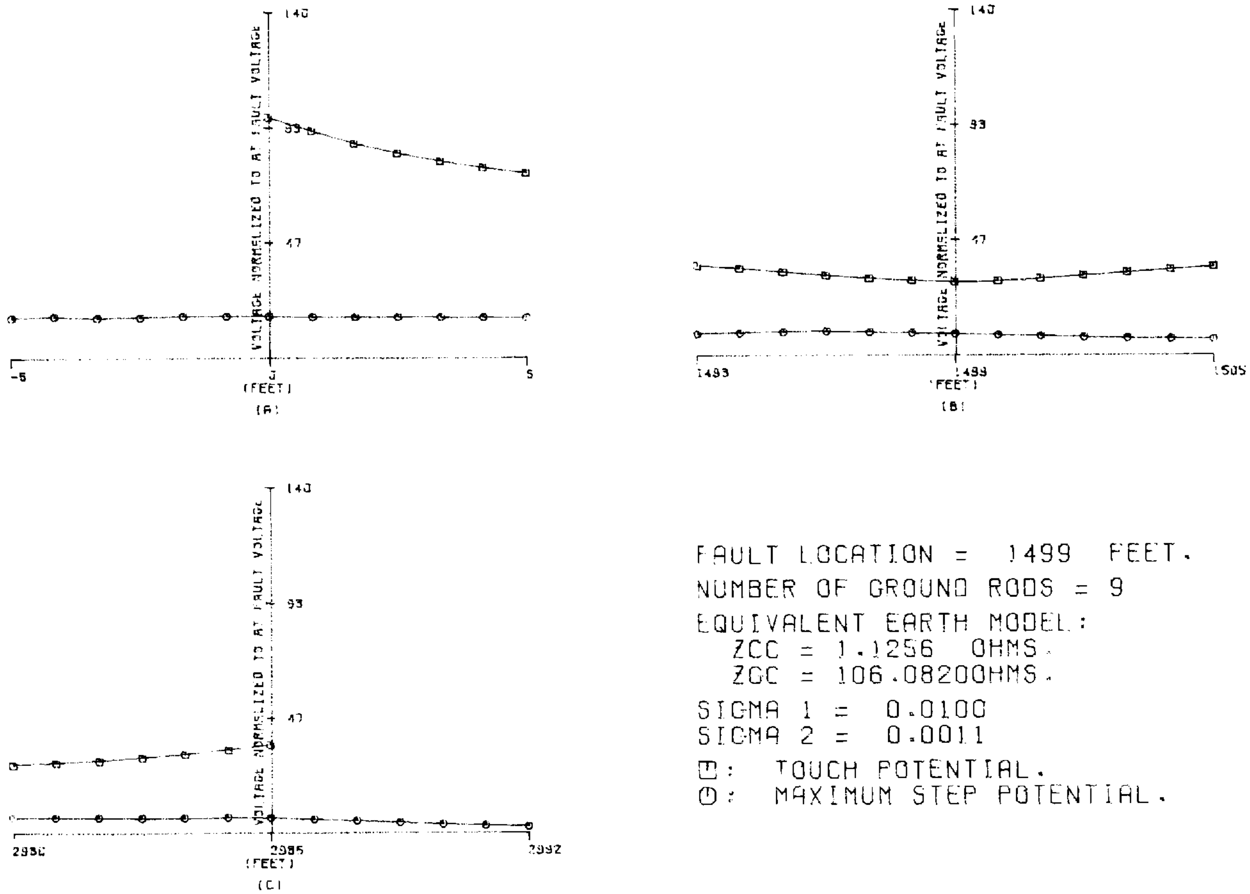


FIGURE B.140 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

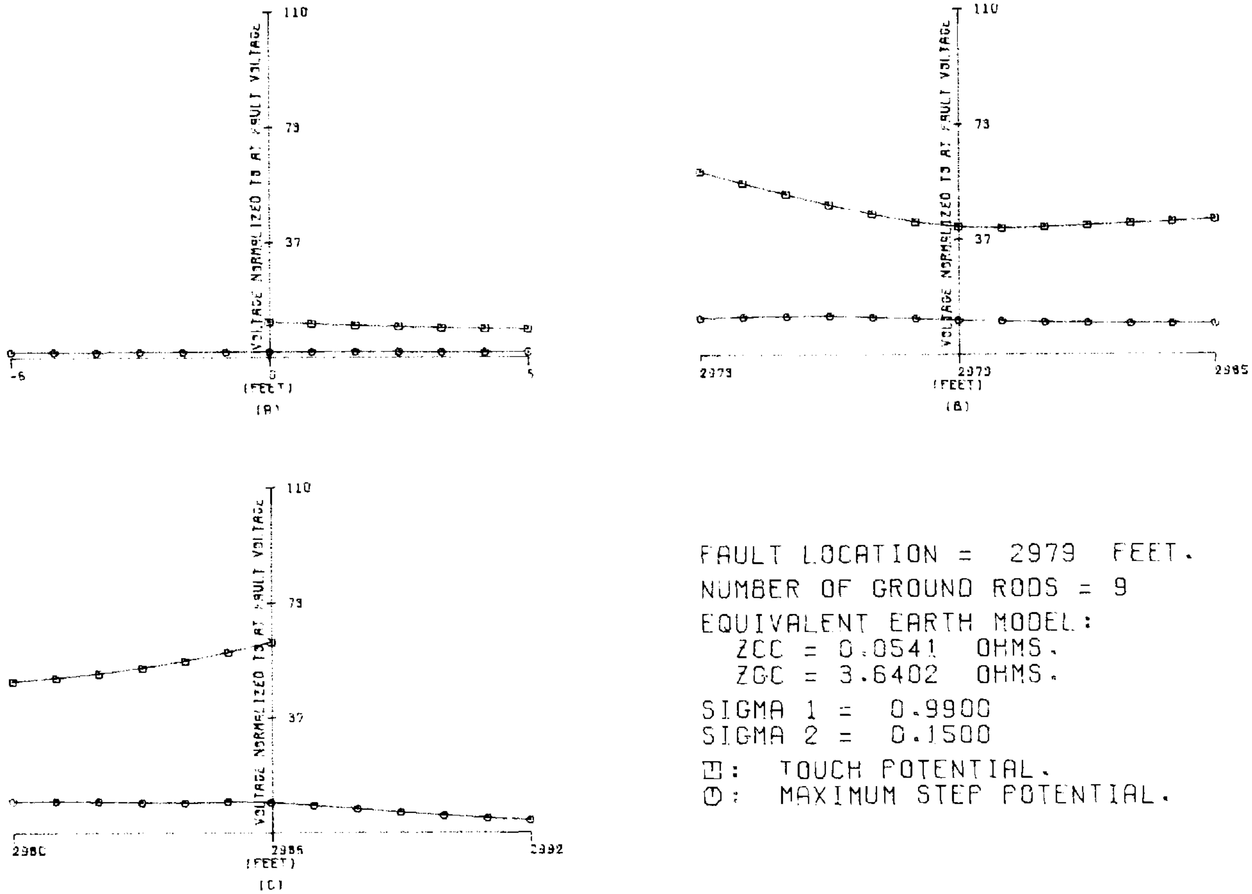
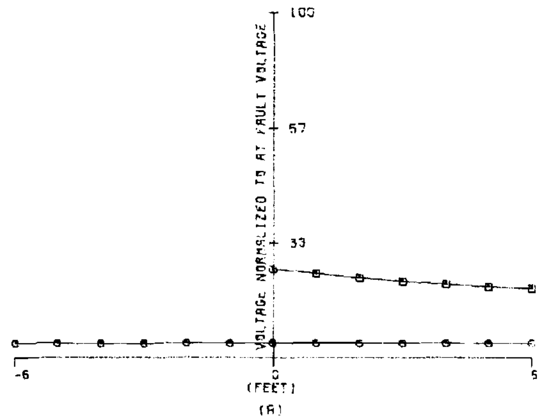
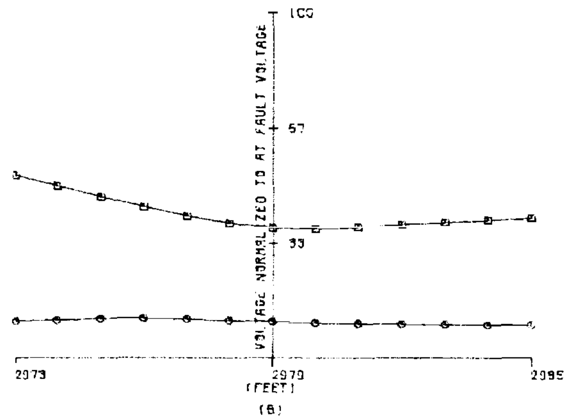
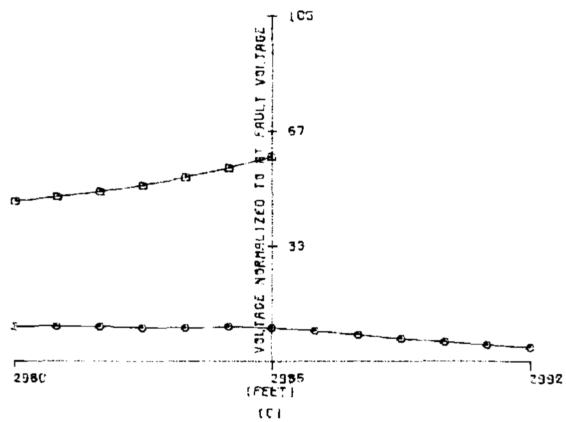


FIGURE B.141 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

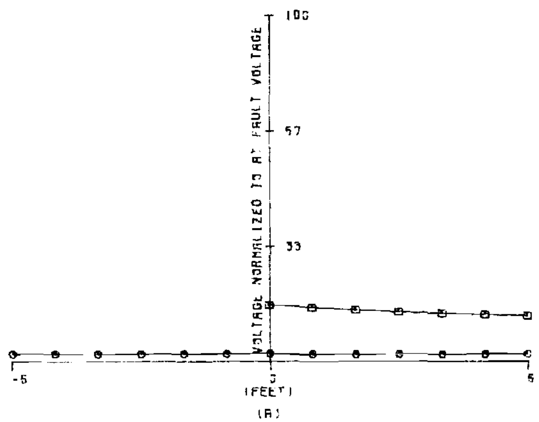


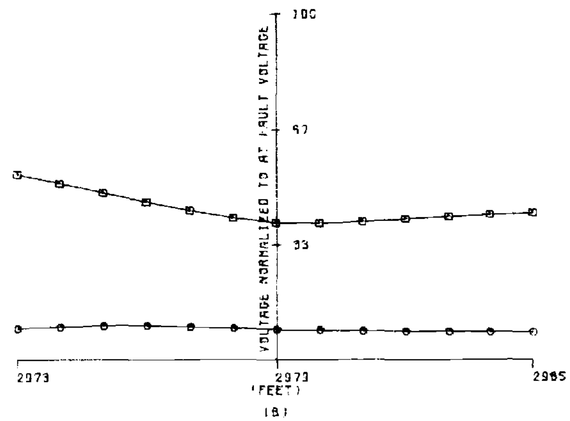


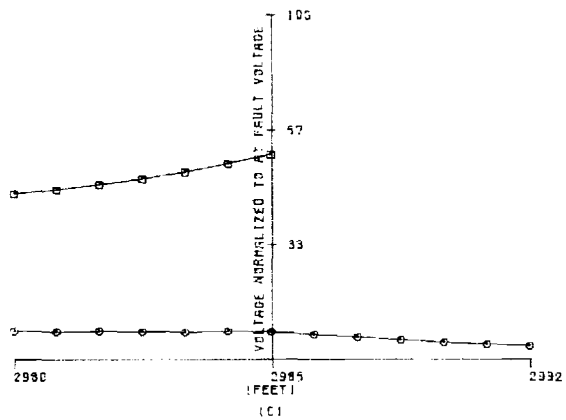


FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1950 OHMS.
ZGC = 12.7608 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
◻: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.142 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

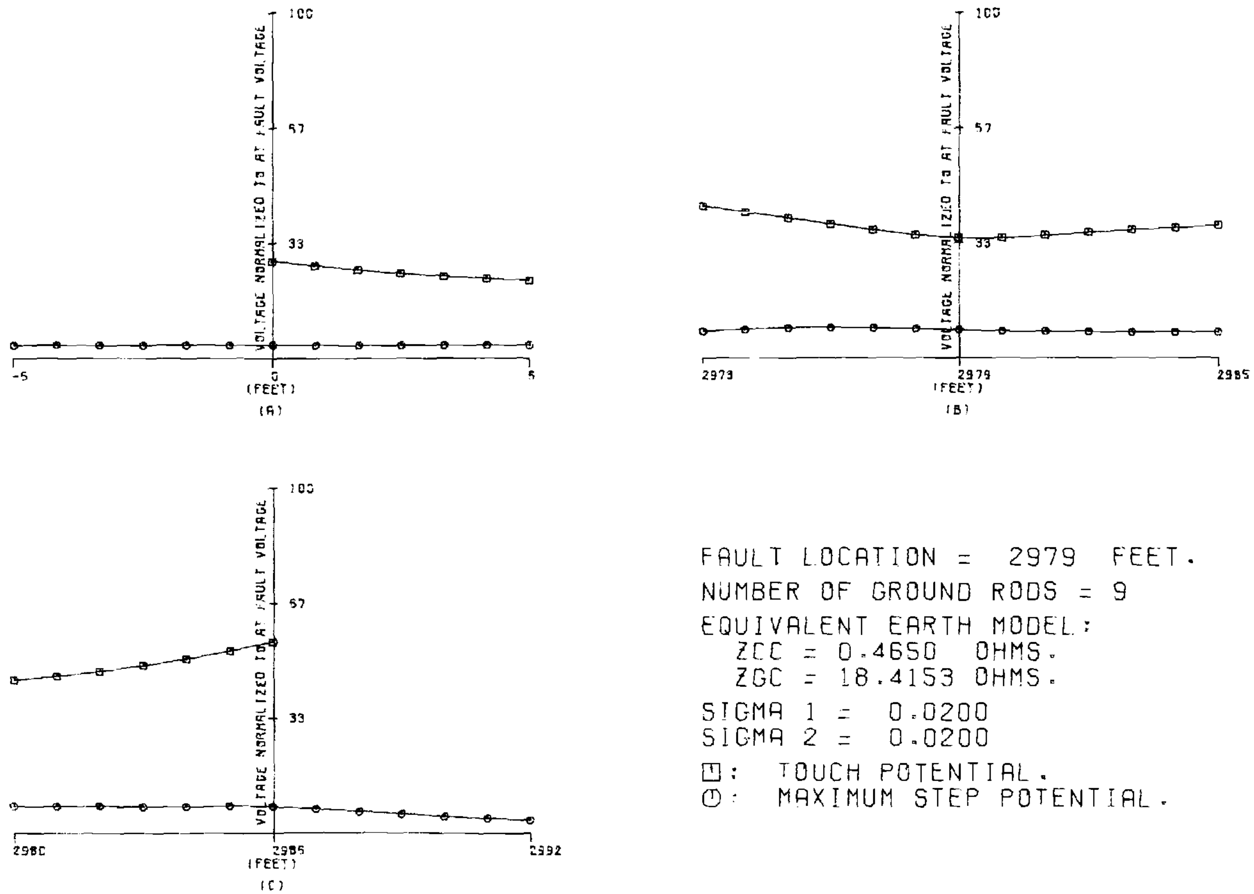






FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.1595 OHMS.
ZGC = 5.8489 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.143 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.



FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.4650 OHMS.
ZGC = 18.4153 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.144 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

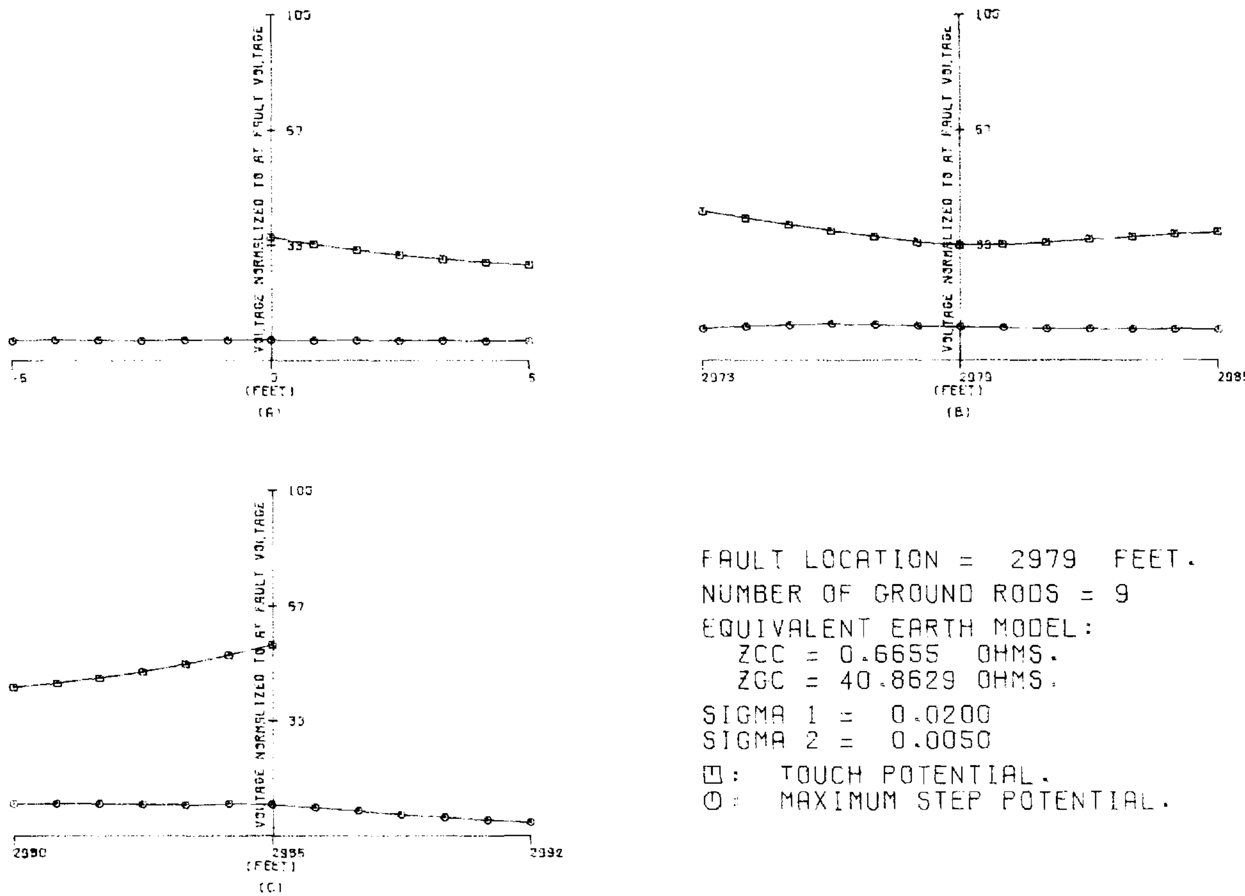
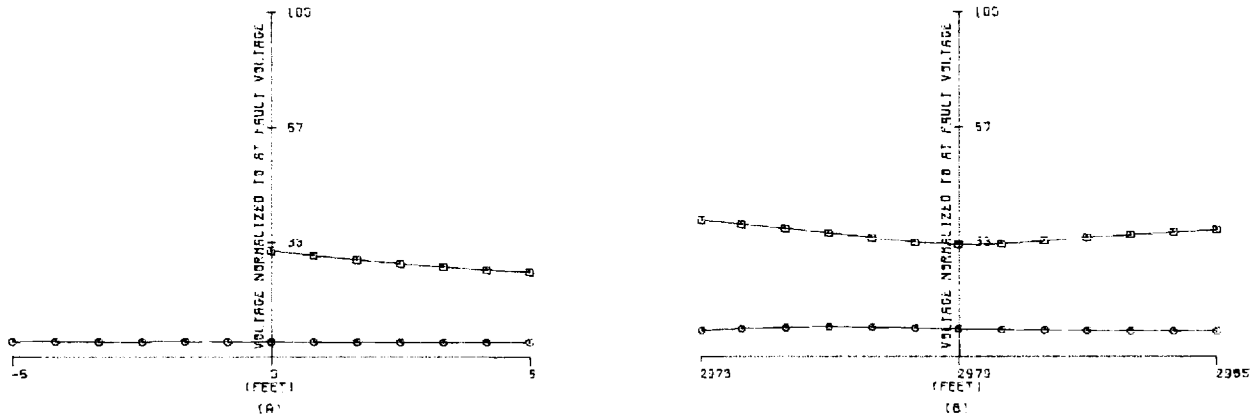
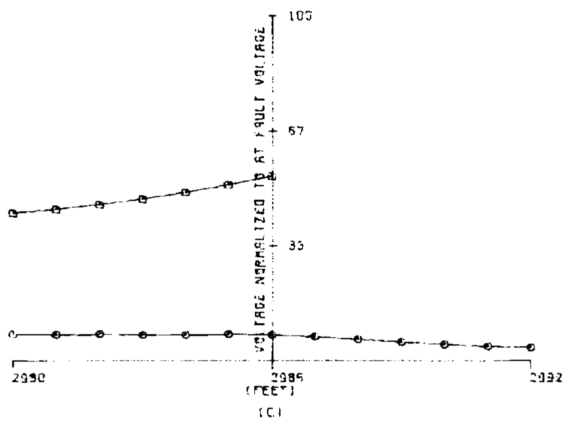


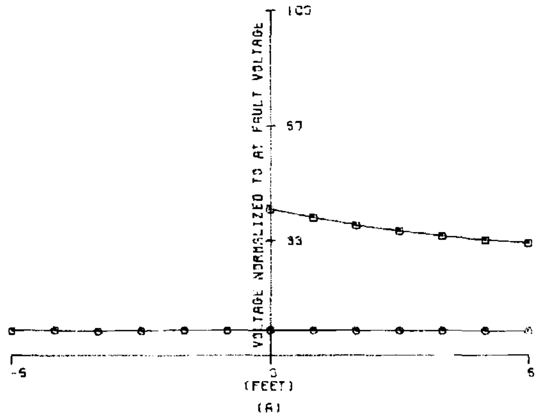
FIGURE B.145 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

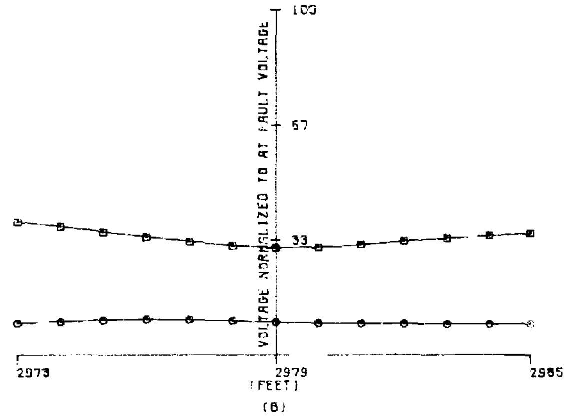


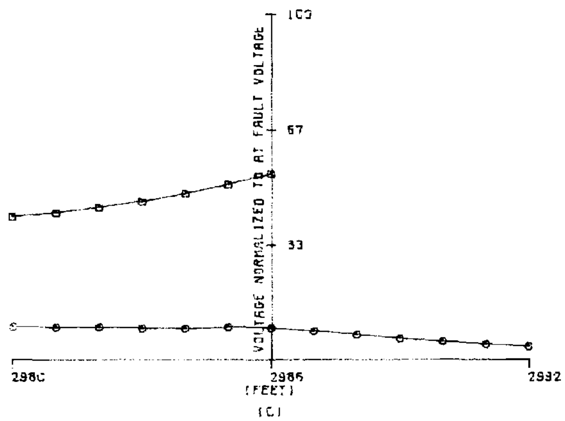


FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 0.8715 OHMS.
ZGC = 34.6095 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.146 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

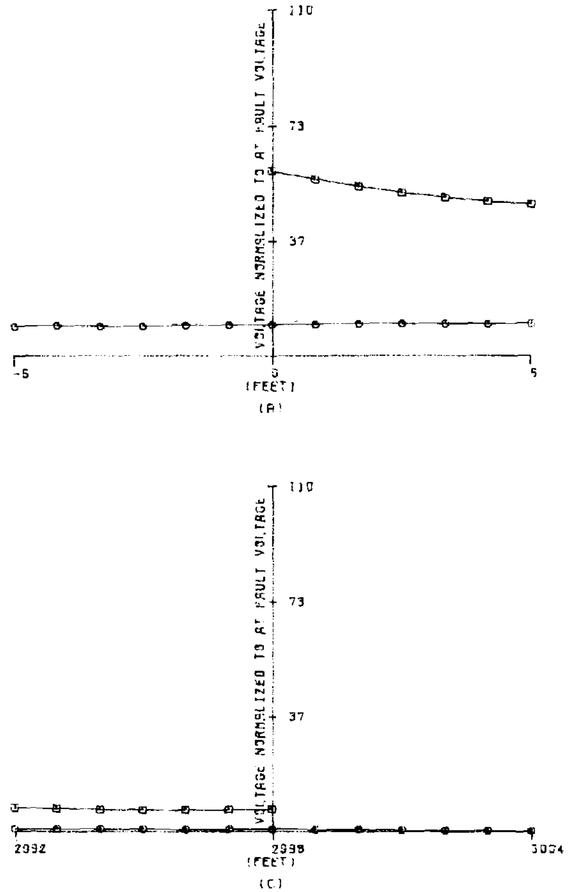






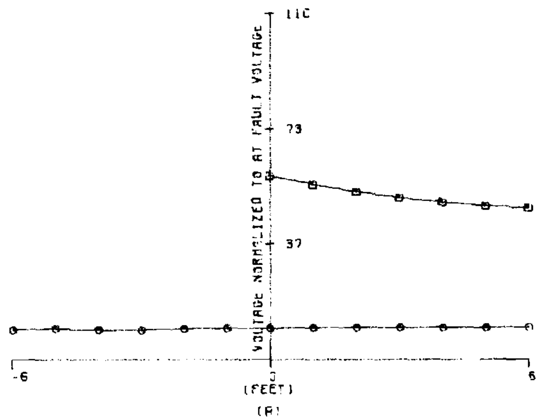
FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 9
EQUIVALENT EARTH MODEL:
ZCC = 1.9281 OHMS.
ZGC = 173.1298OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

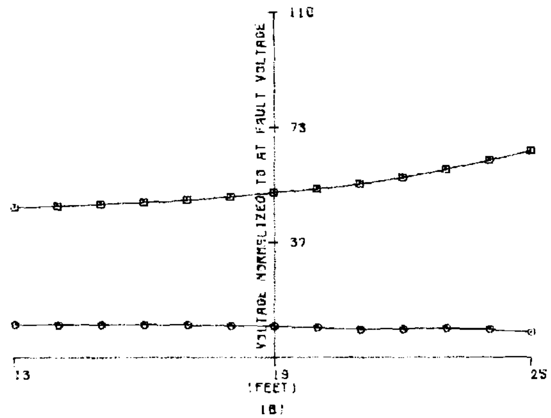
FIGURE B.147 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

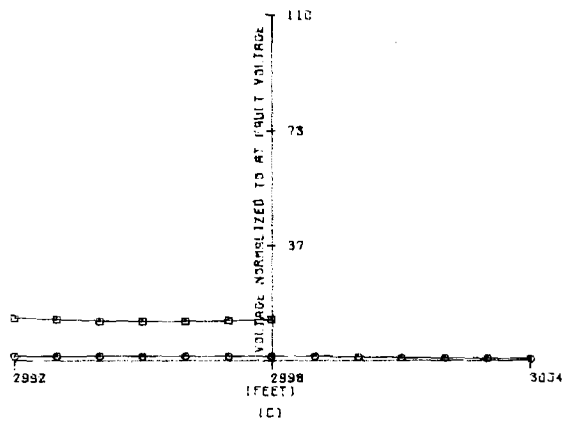


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.0843 OHMS.
ZGC = 5.4878 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.148 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

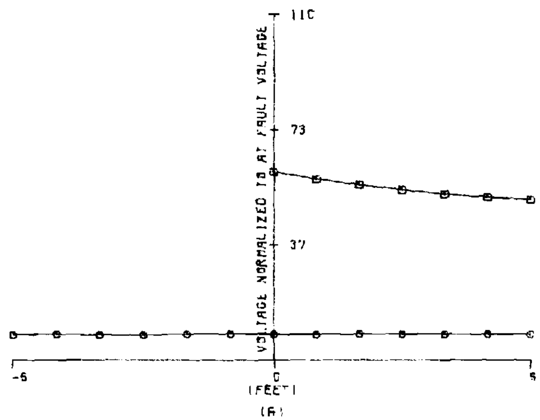


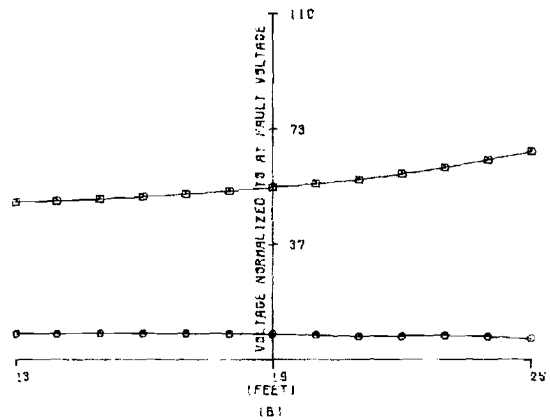


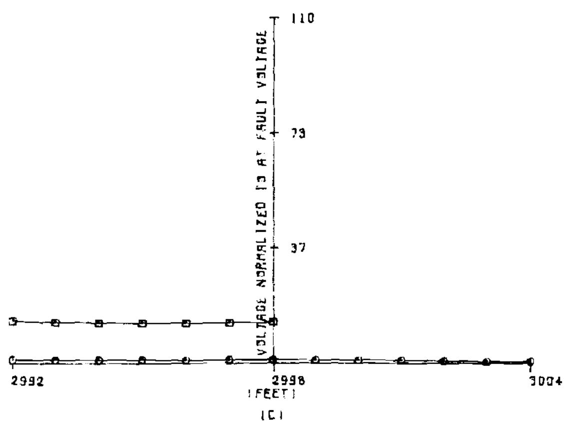


FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1780 OHMS.
ZGC = 11.7172 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
◫: TOUCH POTENTIAL.
⦶: MAXIMUM STEP POTENTIAL.

FIGURE B.149 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1469 OHMS.
ZGC = 5.6966 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.150 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

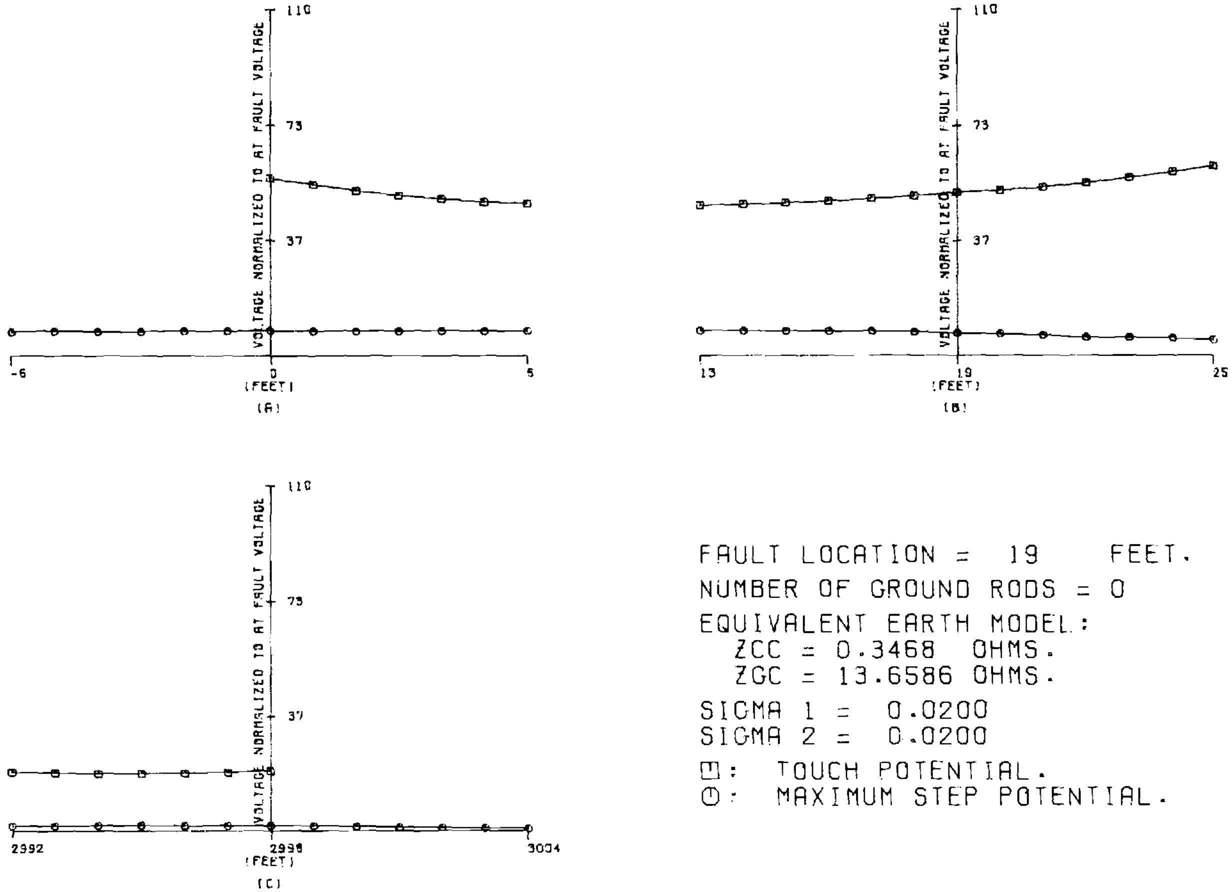
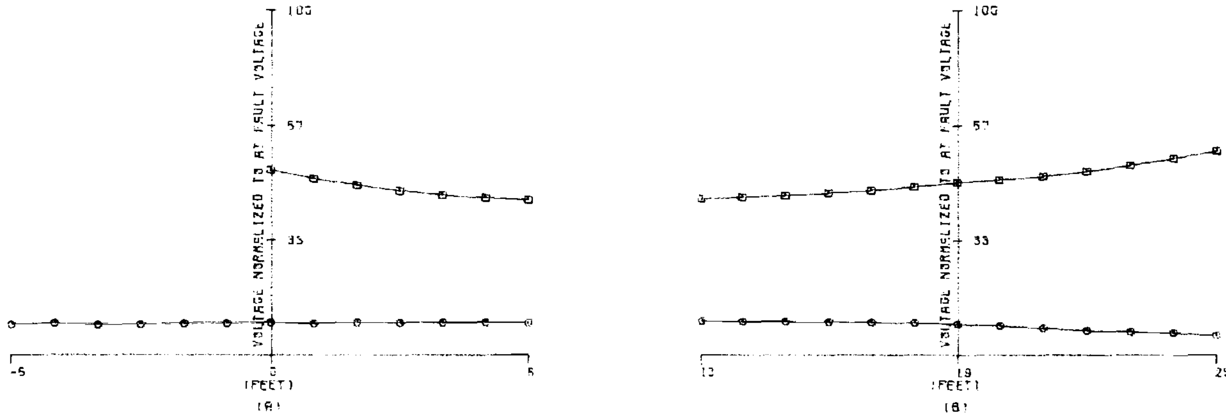
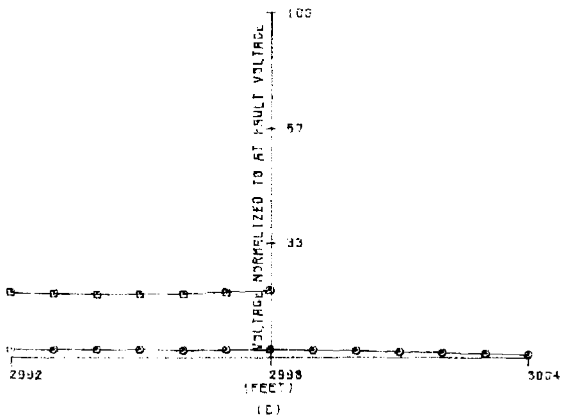


FIGURE B.151 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 19 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.4072 OHMS.
ZGC = 25.8735 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.152 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

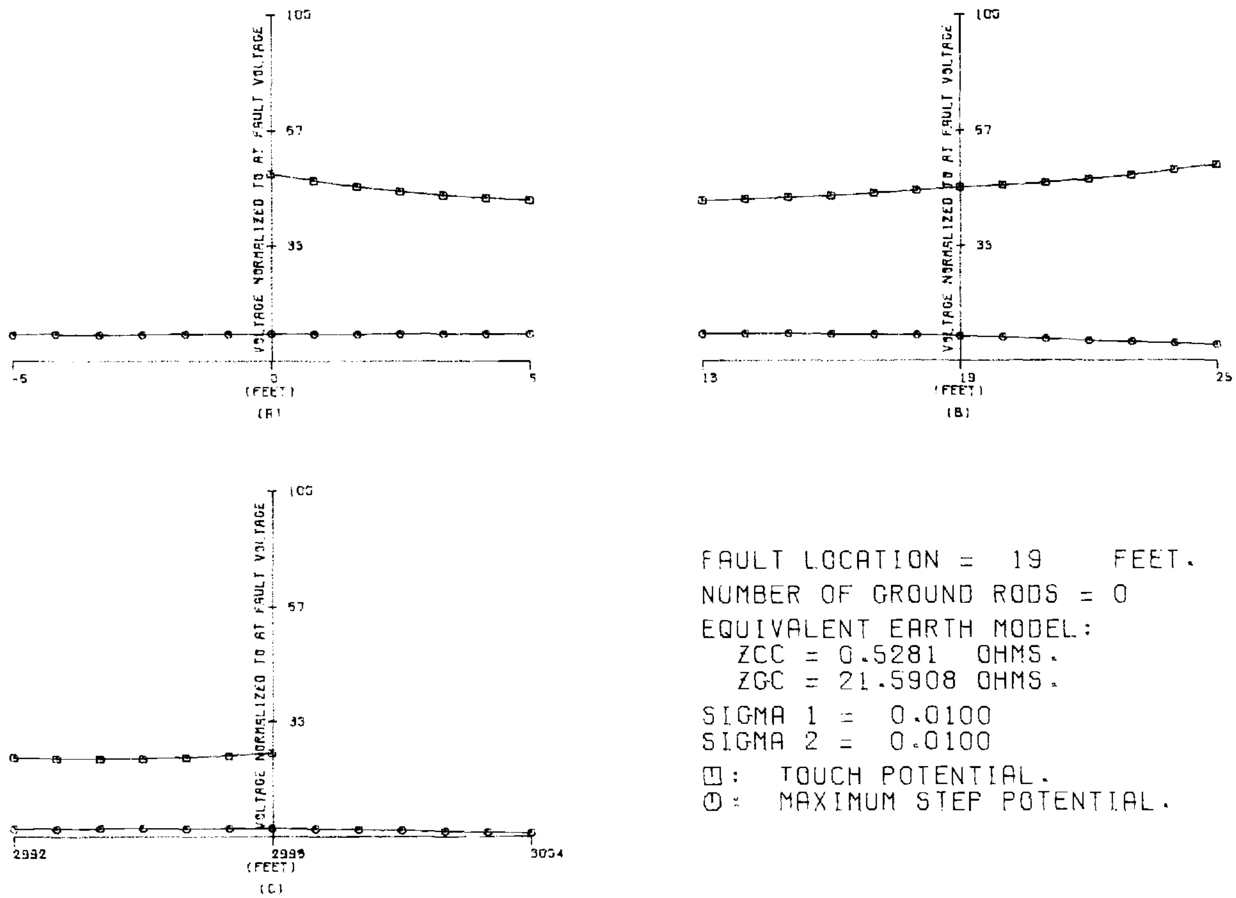


FIGURE B.153 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

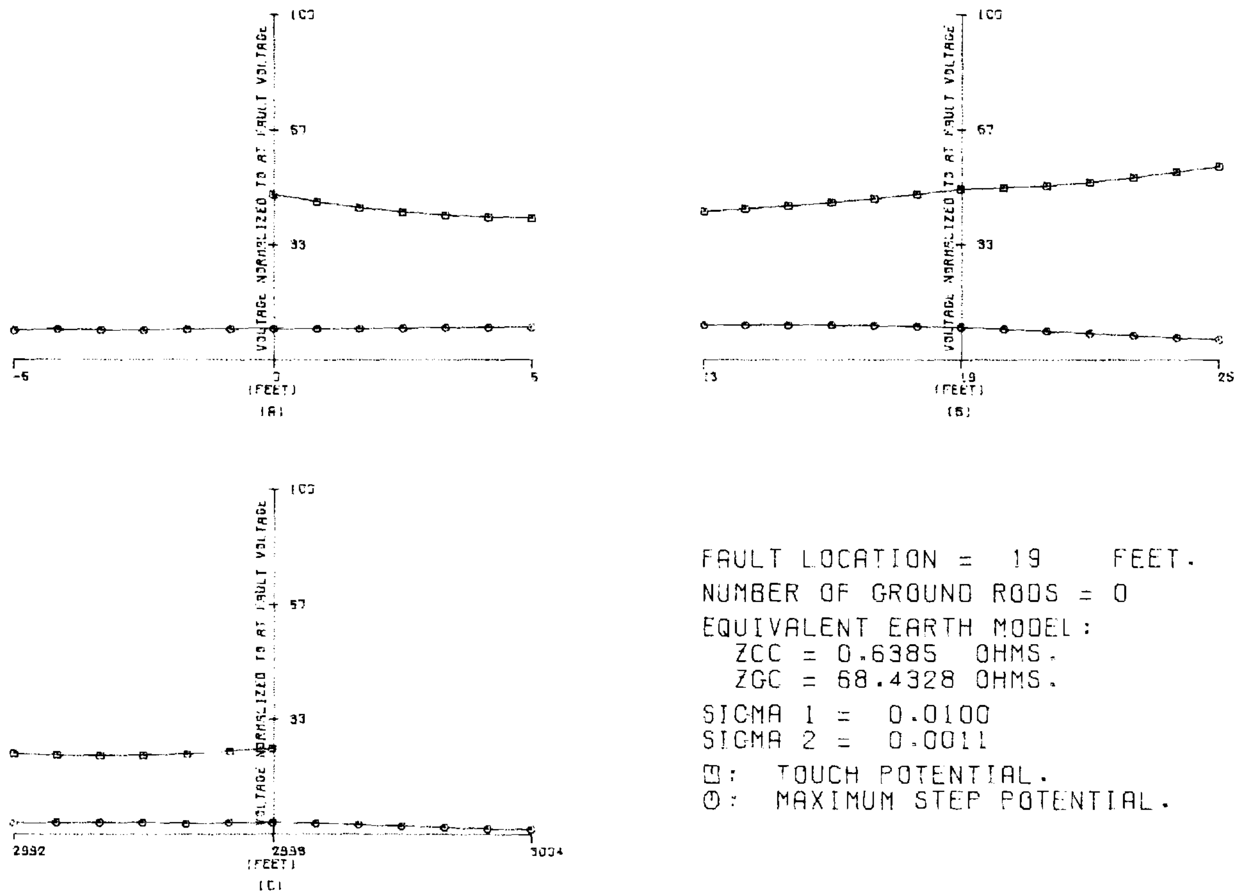
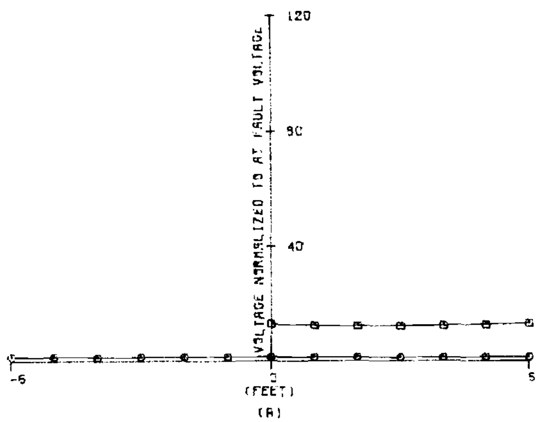
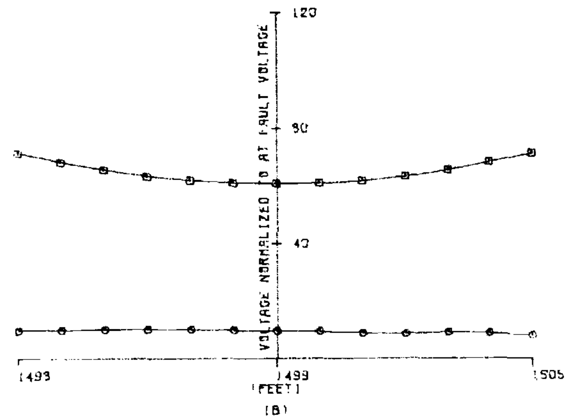
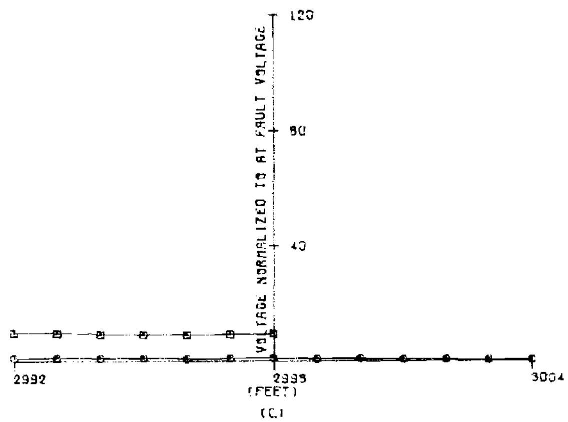


FIGURE B.154 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

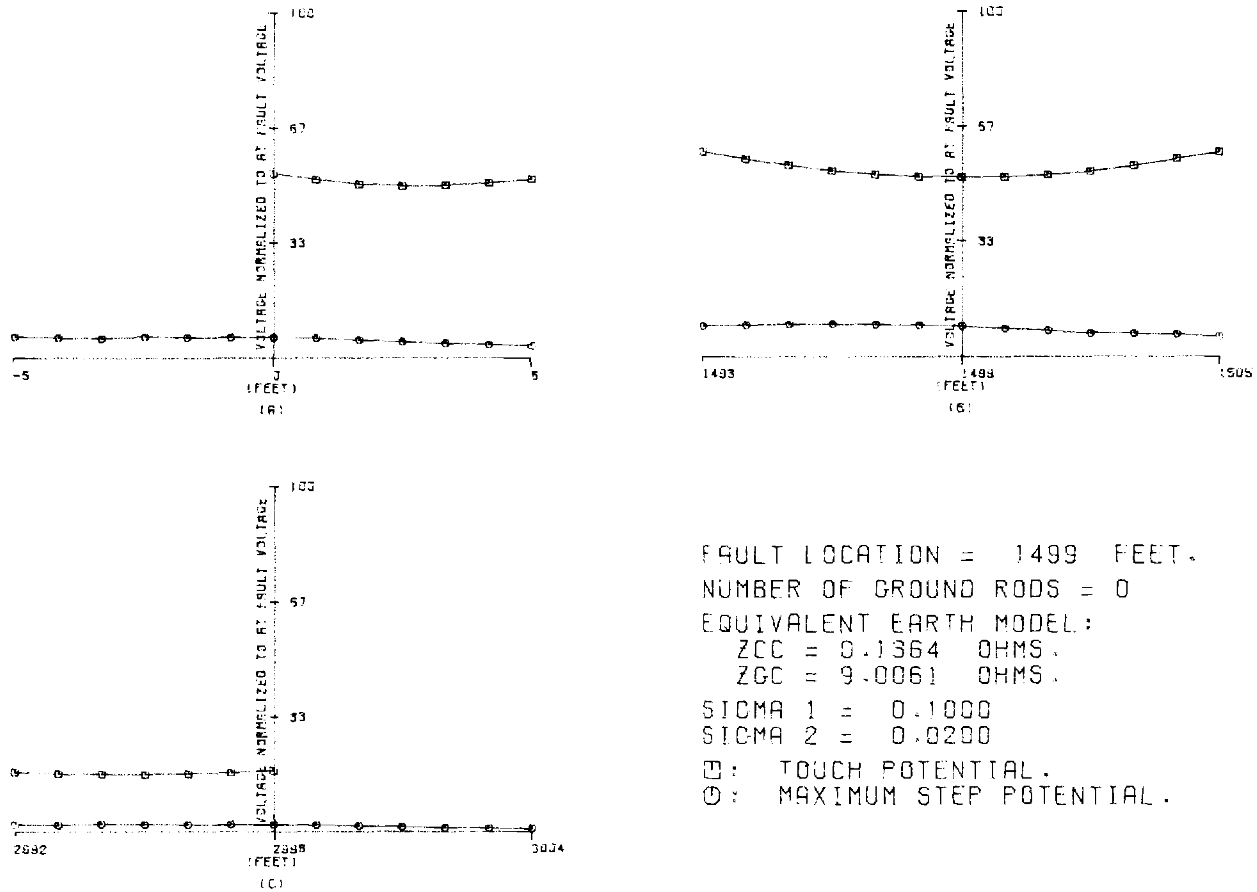






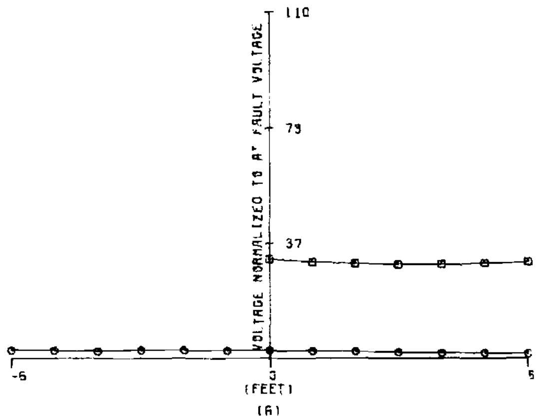
FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.0705 OHMS.
ZGC = 4.5913 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

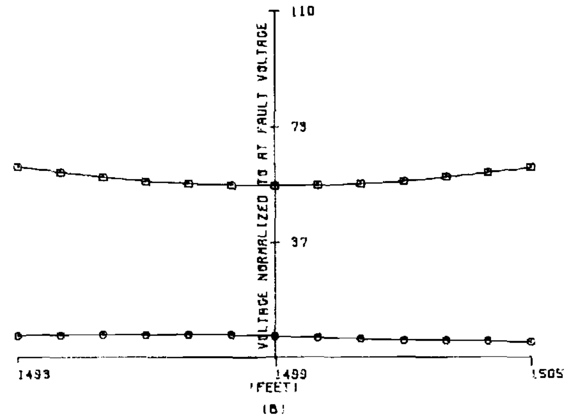
FIGURE B.155 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

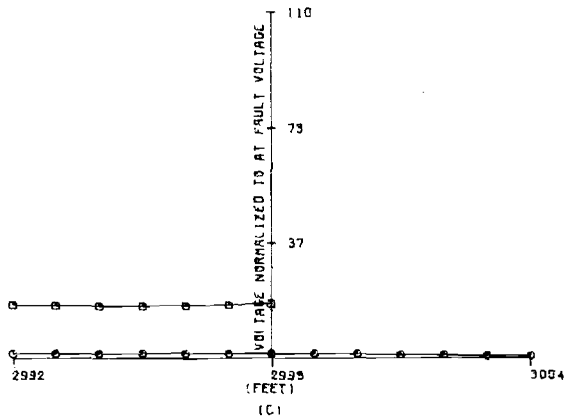


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1364 OHMS.
ZGC = 9.0061 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.0200
⊡: TOUCH POTENTIAL.
⊙: MAXIMUM STEP POTENTIAL.

FIGURE B.156 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

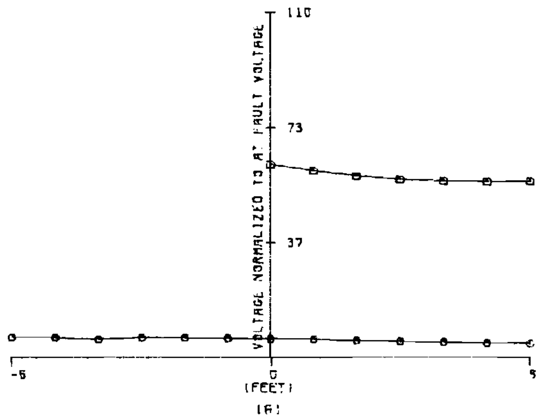


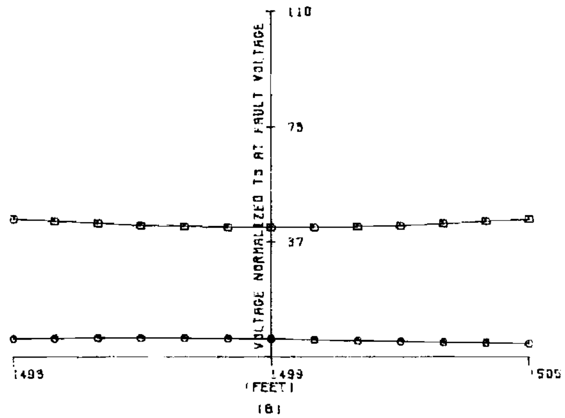


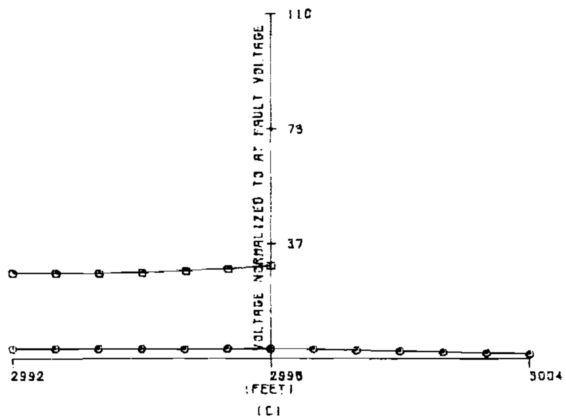


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.1156 OHMS.
ZGC = 4.1695 OHMS.
SIGMA 1 = 0.1000
SIGMA 2 = 0.1000
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.157 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

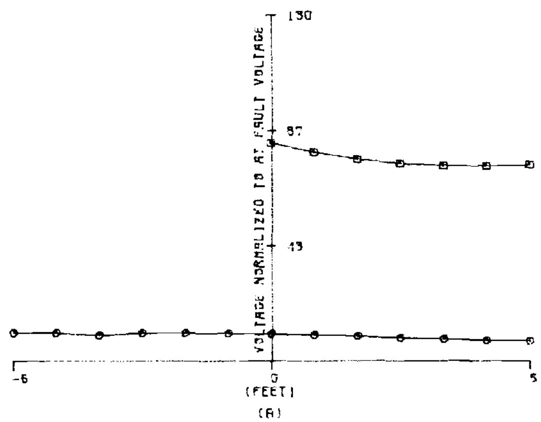


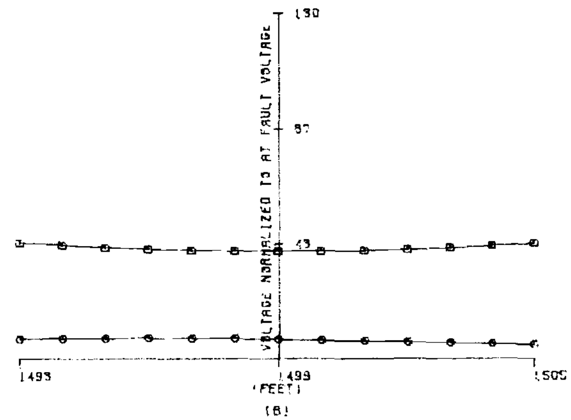


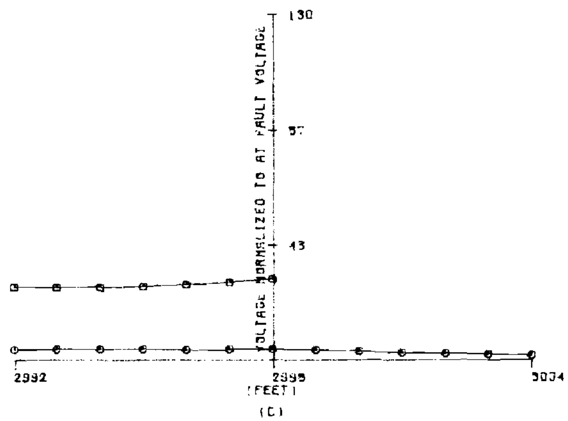


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.3058 OHMS.
ZGC = 12.4075 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0200
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.158 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

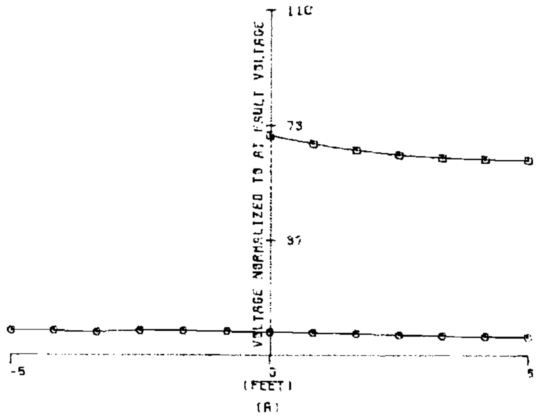


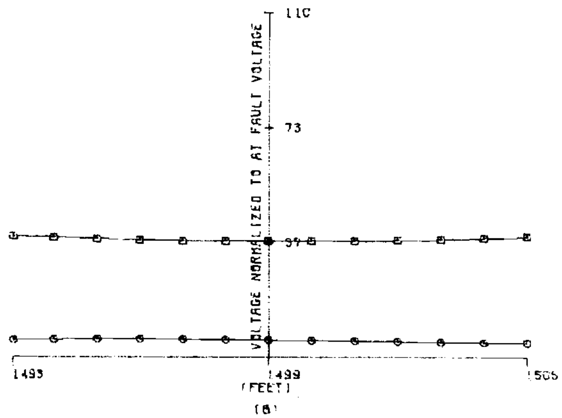


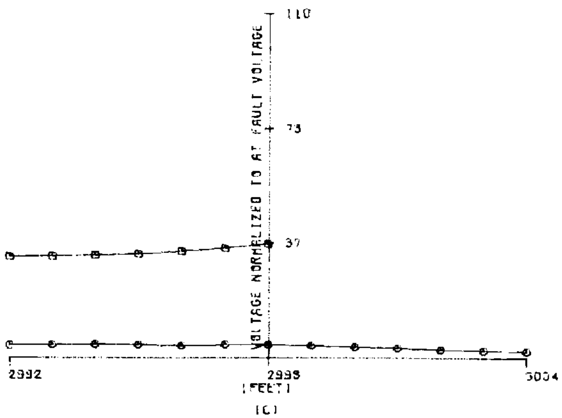


FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.4176 OHMS.
ZGC = 26.8068 OHMS.
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.159 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 1499 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.5571 OHMS.
ZGC = 22.9524 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.160 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

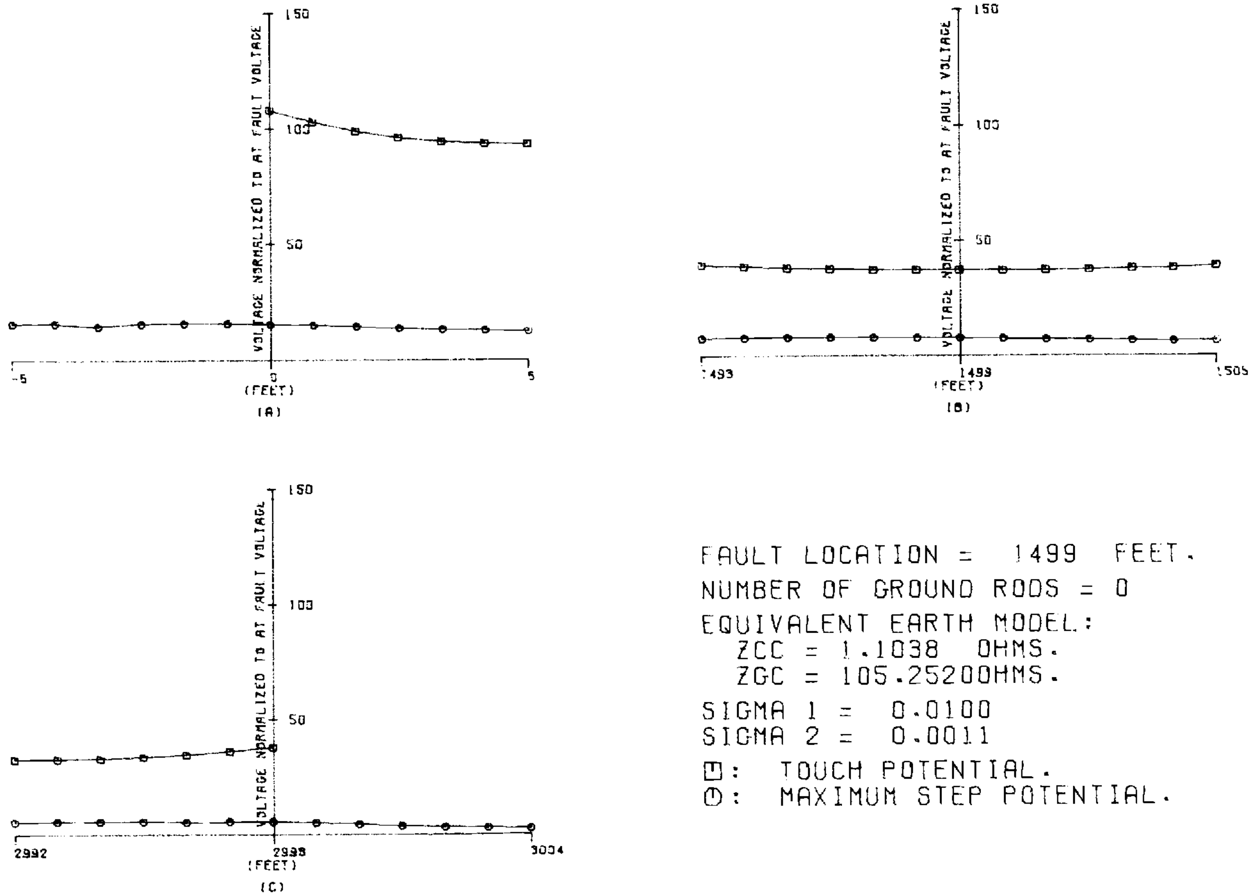
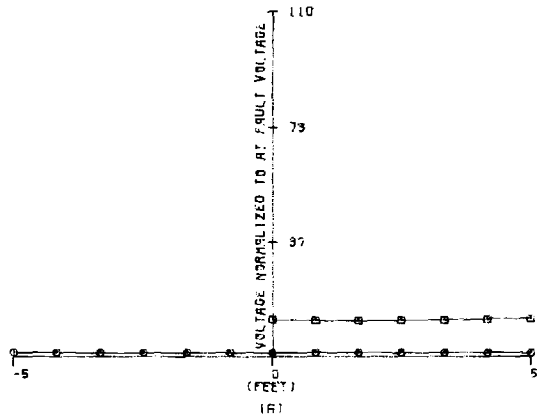
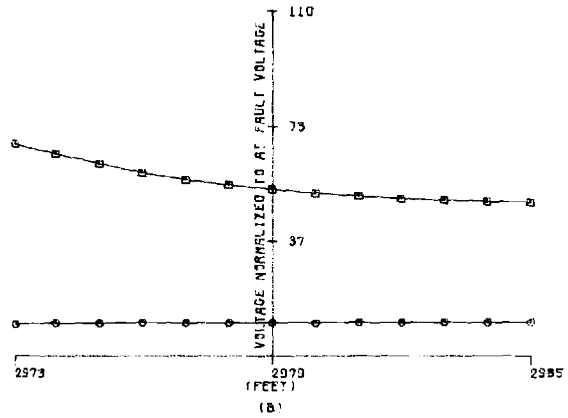
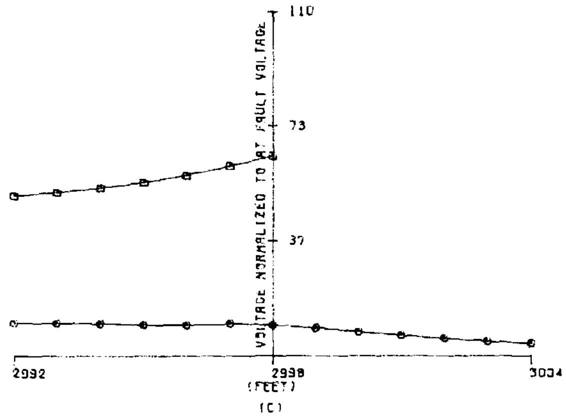


FIGURE B.161 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.0787 OHMS.
ZGC = 5.2610 OHMS.
SIGMA 1 = 0.9900
SIGMA 2 = 0.1500
□: TOUCH POTENTIAL.
O: MAXIMUM STEP POTENTIAL.

FIGURE B.162 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

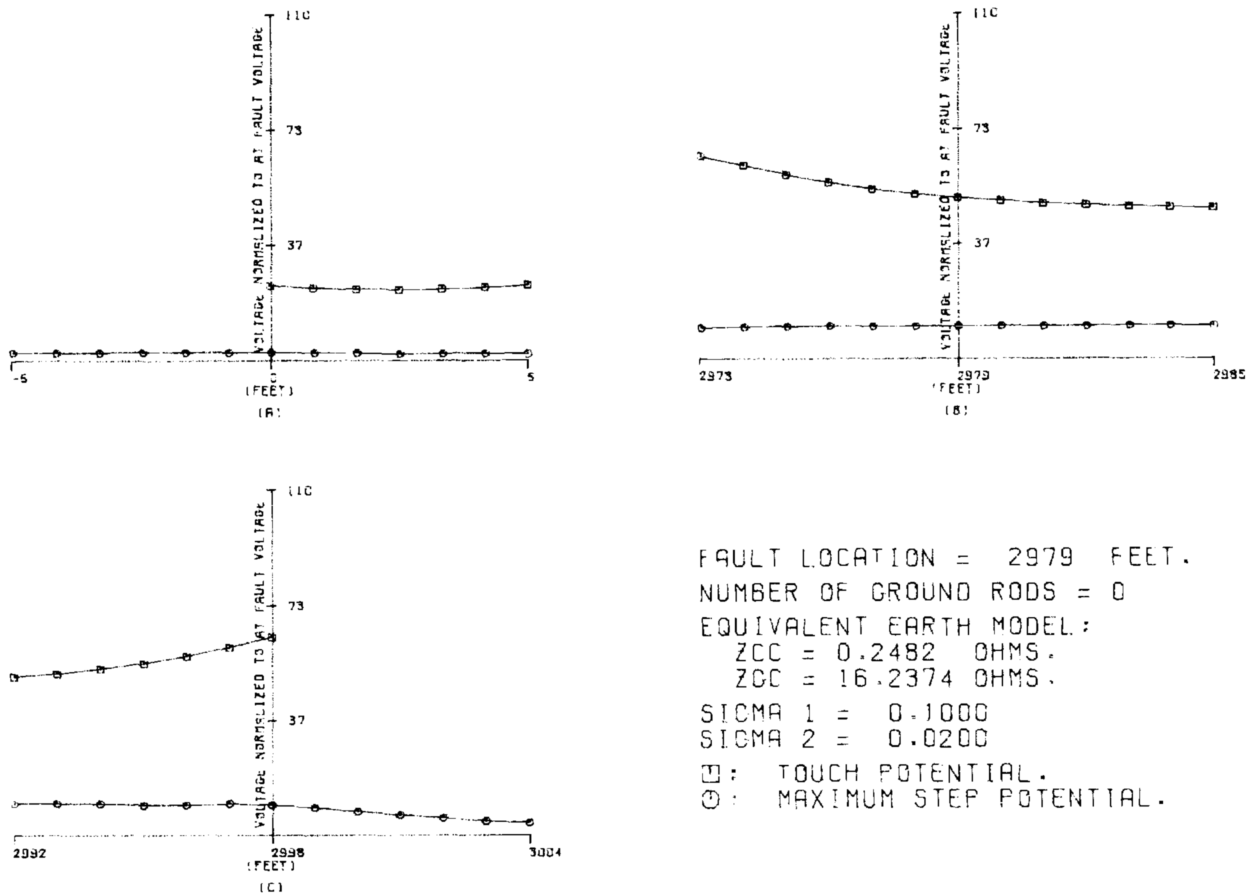


FIGURE B.163 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

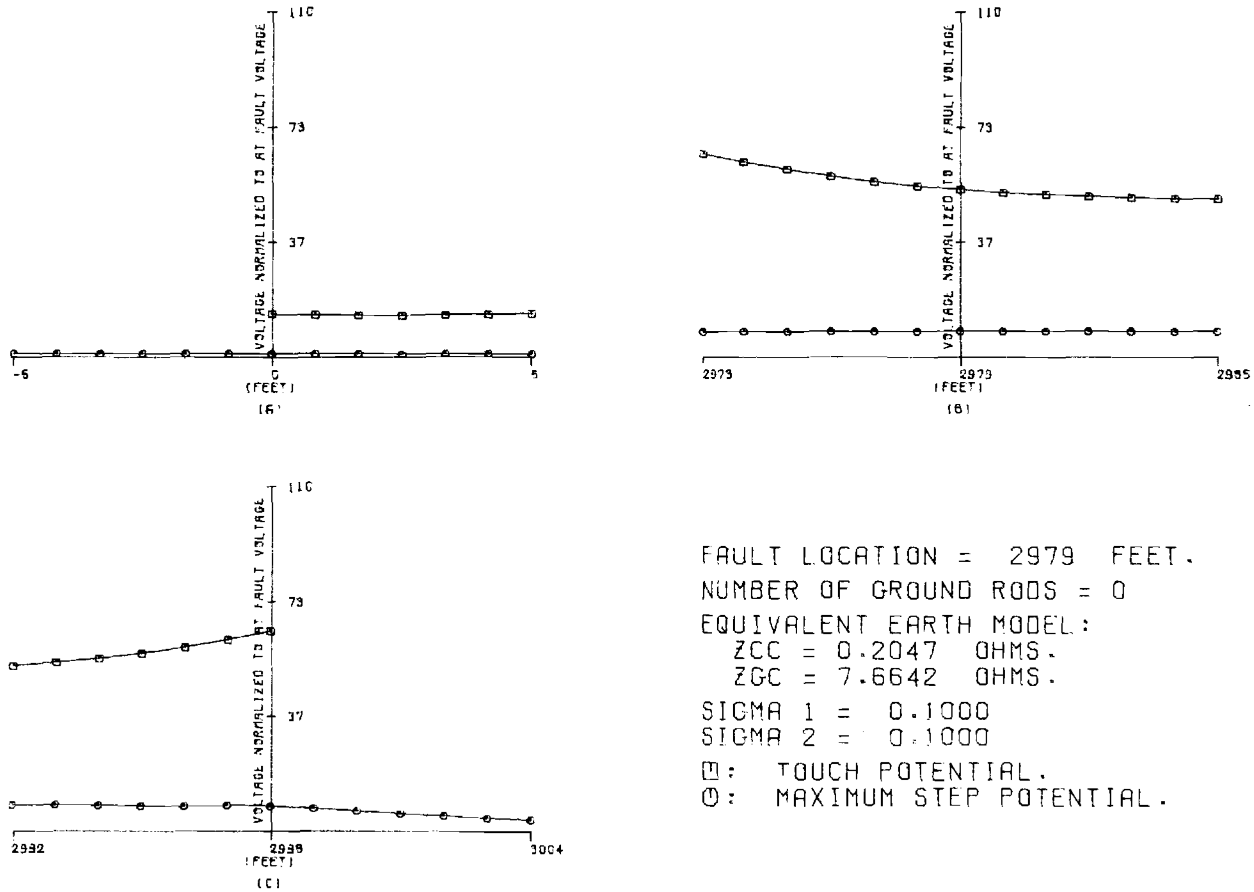


FIGURE B.164 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

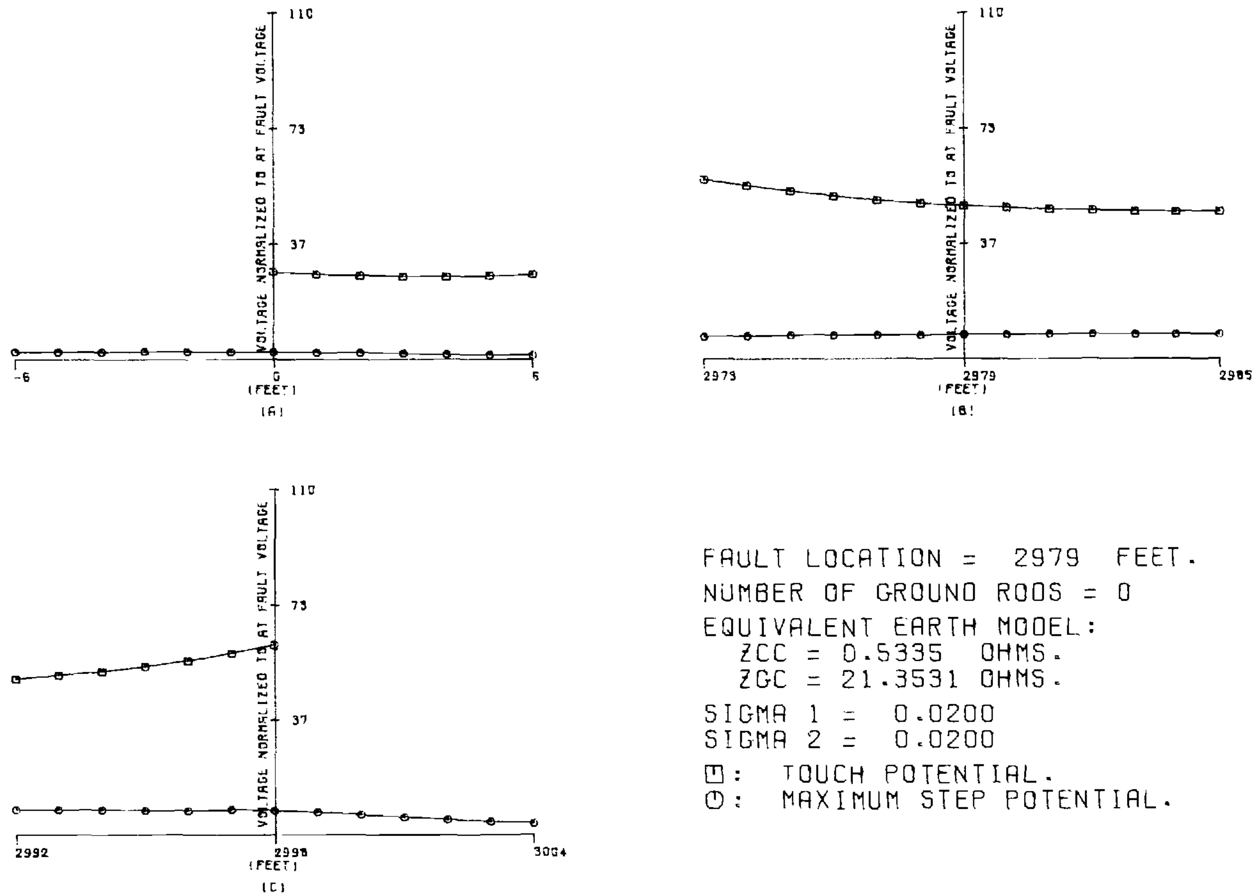
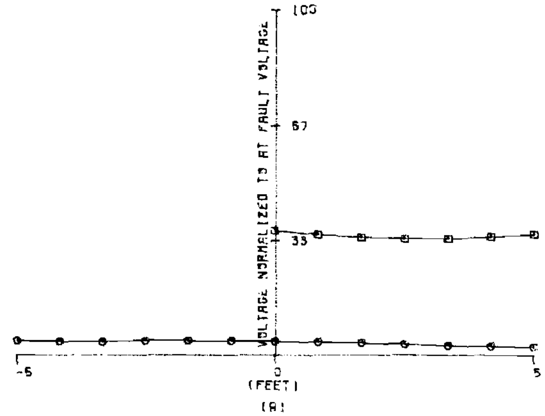
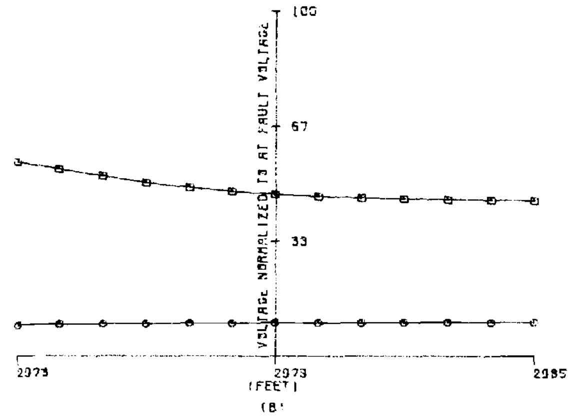
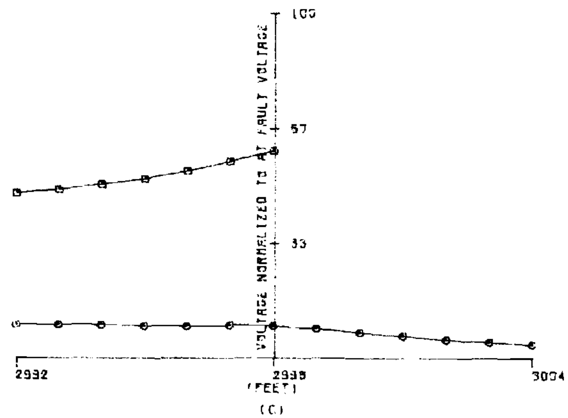


FIGURE B.165 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.







FAULT LOCATION = 2979 FEET.

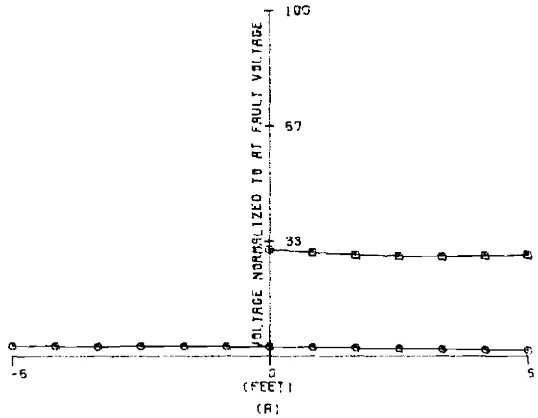
NUMBER OF GROUND RODS = 0

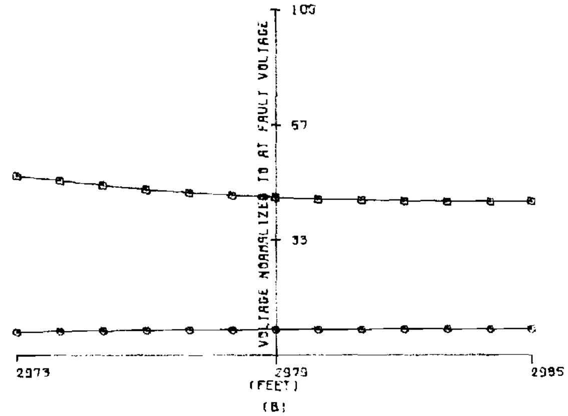
EQUIVALENT EARTH MODEL:
ZCC = 0.7536 OHMS.
ZGC = 46.4025 OHMS.

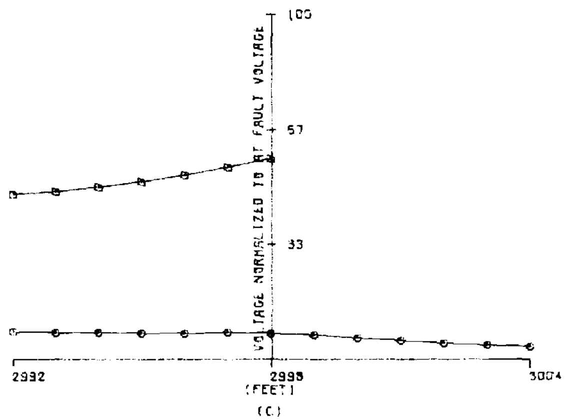
SIGMA 1 = 0.0200
SIGMA 2 = 0.0050

□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.166 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

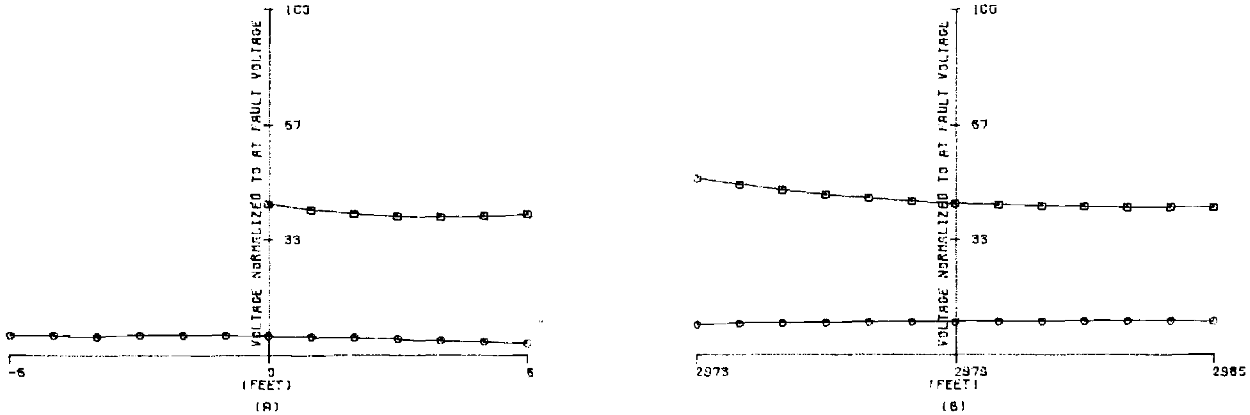


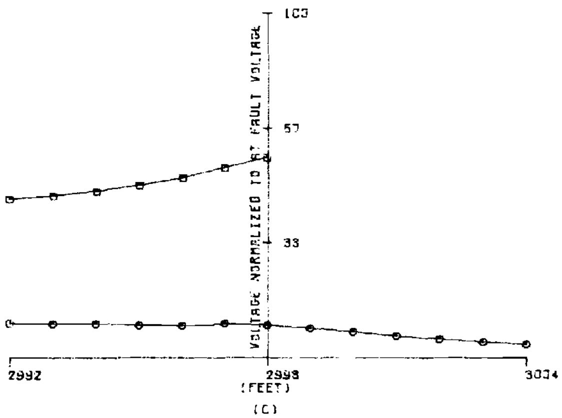




FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 0.9682 OHMS.
ZGC = 38.9076 OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0100
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.167 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.





FAULT LOCATION = 2979 FEET.
NUMBER OF GROUND RODS = 0
EQUIVALENT EARTH MODEL:
ZCC = 2.1107 OHMS.
ZGC = 190.3433OHMS.
SIGMA 1 = 0.0100
SIGMA 2 = 0.0011
□: TOUCH POTENTIAL.
○: MAXIMUM STEP POTENTIAL.

FIGURE B.168 TOUCH AND STEP POTENTIALS:
A) NEAR SOURCE END OF CABLE.
B) NEAR FAULT.
C) NEAR CABLE END.

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Below are five index cards that allow for filing according to the four cross-references in addition to the title of the report. A brief abstract describing the major subject area covered in the report is included on each card. For information regarding index card subscriptions to past and future EPRI publications contact the Research Reports Center, P.O. Box 50490, Palo Alto, California 94303. Telephone (415) 965-4081.

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Cross-references:
1. EPRI EL-1605, Volume 2 2. RP797-2 3. Distribution Program 4. Cable

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